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What Lawmakers Can Learn from Large-Scale Ecology

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A shorter version of this article was presented as a lecture at The Florida State University College of Law, and the article has benefited from the comments received from those in attendance and from my esteemed colleague, Dan Tarlock. The research has been supported by a grant from the Marshall Ewell Research Fund. This article is dedicated to May Thielgaard Watts.

WHAT LAWMAKERS CAN LEARN FROM LARGE-SCALE ECOLOGY

FRED BOSSELMAN*

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I. INTRODUCTION: SCALE IN ECOLOGY

In the science of ecology, "scale" refers to both space and time. Today, ecological scientists have dramatically expanded their ability to study the natural world in large quantities, both spatially and temporally.[1] The results of this research should lead us to

* Professor of Law, Chicago-Kent College of Law. A shorter version of this article was presented as a lecture at The Florida State University College of Law, and the article has benefitted from the comments received from those in attendance and from my esteemed colleague, Dan Tarlock. The research has been supported by a grant from the Marshall Ewell Research Fund. This article is dedicated to May Thielgaard Watts.

1. For a summary of the way the term "scale" is used in ecology, *see* MONICA G. TURNER ET AL., LANDSCAPE ECOLOGY IN THEORY AND PRACTICE 25-30 (2001). The work of ecologists has been done in combination with specialists in many other fields that emphasize large scale analysis. *See, e.g.*, NAT'L ASSESSMENT SYNTHESIS TEAM, U.S. GLOBAL CHANGE RESEARCH PROGRAM, CLIMATE CHANGE IMPACTS ON THE UNITED STATES 76-80 (2001) (discussing biochemistry and biogeography models used to consider ecological impact of

question some of the old theories implanted in popular ideas about ecology and to explore new ideas that raise new concerns about the ways in which humans are affecting nature.

A. *Geographic Scale*

Advances in the technology of information gathering and processing have enabled ecological scientists to study the natural world on a larger scale than ever before. Where ecologists were once limited to studying an individual bog or a hilltop, they can now study entire regions or continents.[2]

1. Remote Sensing

Data from satellite observations has become increasingly sophisticated and widely available,[3] enabling ecologists to map the characteristics of areas for which field data is sparse,[4] and offering new opportunities to develop techniques for mapping species' range[5] and classifying ecological systems.[6]

Today's satellite maps cover the globe, revealing the distribution of types of ecological systems at increasingly higher resolutions.[7]

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climate change).

2. "Treating each ecosystem individually, as we now do, loses track of important processes and fluxes that occur at the interfaces. Because ecosystems often occur as a patchwork on the landscape, outputs from one system are almost always inputs to another. Only by treating the entire landscape as a system can all of the important system properties be evaluated." Stephen L. Rawlins, *Institutional Capacity to Monitor the Sources and Effects of Environmental Change in Agriculture*, *in* AGRICULTURE, ENVIRONMENT, AND HEALTH: SUSTAINABLE DEVELOPMENT IN THE 21ST CENTURY 261, 276-77 (Vernon W. Ruttan ed., 1994).

3. KRISTIINA A. VOGT ET AL. EDS., ECOSYSTEMS: BALANCING SCIENCE WITH MANAGEMENT 220-23 (1997). The new and projected advances in remote sensing technology using satellites are concisely summarized in NAT'L RESEARCH COUNCIL, ECOLOGICAL INDICATORS FOR THE NATION 34-41 (2000). *See generally* JOHN R. SCHOTT, REMOTE SENSING: THE IMAGE CHAIN APPROACH (1996); PETER A. BURROUGH & RACHAEL A. MCDONNELL, PRINCIPLES OF GEOGRAPHICAL INFORMATION SYSTEMS (2d ed., 1998); Woody Turner et al., *Special Section: Contributions of Remote Sensing to Biodiversity Conservation: A NASA Approach*, 15 CONSERVATION BIOLOGY 832 (2001). For visual examples, visit NASA Goddard Space Flight Center, GSFC on-line News Releases *available at* http://www.gsfc.nasa.gov/gsfc/earth/imaging/landsat.htm (last visited Mar. 7, 2002).

4. *See, e.g.*, Giles M. Foody et al., *Mapping the Biomass of Bornean Tropical Rain Forest from Remotely Sensed Data*, 10 GLOBAL ECOLOGY & BIOGEOGRAPHY 379 (2001). *See generally*, MAPPING THE DIVERSITY OF NATURE (Ronald I. Miller ed., 1994).

5. Bruce A. Stein & Frank W. Davis, *Discovering Life in America: Tools and Techniques of Biodiversity Inventory*, *in* PRECIOUS HERITAGE: THE STATUS OF BIODIVERSITY IN THE UNITED STATES 19, 21-23 (Bruce A. Stein et al. eds., 2000).

6. R.S. Defries & J.R.G. Townshend, *Global Land Cover Characterization from Satellite Data: From Research to Operational Implementation?*, 8 GLOBAL ECOLOGY AND BIOGEOGRAPHY 367 (1999).

7. NAT'L RESEARCH COUNCIL, GRAND CHALLENGES IN ENVIRONMENTAL SCIENCES 25 (2001). The history of the use of remote sensing satellites is summarized *in* Charles Davies et al., *Moving Pictures: How Satellites, the Internet, and International Environmental Law*

Satellite maps provide visual, radar, and infrared images of the land, water, atmosphere, and geophysical images of the shallow subsurface.[8] The current generation of school children are being taught to use geographic information systems in elementary and high schools.[9]

Ecologists are also able to use new technologies to follow the flow of matter and organisms through ecological systems.[10] For example, recent studies have shown for the first time the migration habits of tuna in the Atlantic Ocean,[11] the extent of regrowth of previously cut tropical forest in Amazonia,[12] and increases of woody vegetation in parts of West Africa that were thought to be experiencing desertification.[13]

2. Access to Remote Places

A variety of technologies have increased scientists' abilities to obtain ecological data from places that were until recently inaccessible.[14] "Deep-sea sampling routinely produces cores from both medium and abyssal depths using remotely controlled

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can help Promote Sustainable Development, 28 Stetson L. Rev. 1091 (1999).

8. NAT'L RESEARCH COUNCIL, *supra* note 7, at 33 (2001). For a review of the uses of remote sensing in the analysis of underground conditions, see generally NAT'L RESEARCH COUNCIL, SEEING INTO THE EARTH: NONINVASIVE CHARACTERIZATION OF THE SHALLOW SUBSURFACE FOR ENVIRONMENTAL AND ENGINEERING APPLICATIONS (2000).

9. RICHARD AUDET & GAIL LUDWIG, GIS IN SCHOOLS 5-12 (2000).

10. Global positioning systems operate through transponders attached to objects moving on the earth's surface that report their data to satellites. Davies et al., *supra* note 7, at 1120.

11. *See, e.g.*, John J. Magnuson et al., *Whose Fish are they Anyway?*, 293 SCI. 1267 (2001) (describing use of two new kinds of electronic tags used to track the movement of tuna throughout the Atlantic Ocean).

12. D.S. Alves & D.L. Skole, *Characterizing Land Cover Dynamics Using Multi-Temporal Imagery*, 17 INT'L J. OF REMOTE SENSING 835 (1996) (stating as much as 31% of formerly cut forest is in various stages of regrowth). For other examples of the use of remote sensing in the analysis of deforestation, see Jaboury Ghazoul & Julian Evans, *Deforestation and Land Clearing*, *in* 2 ENCYCLOPEDIA OF BIODIVERSITY 23, 26 (Simon Asher Levin ed., 2001).

13. Thomas J. Bassett & Koli Bi Zuéli, *Environmental Discources and the Ivorian Savanna*, 90 ANNALS OF THE ASS'N OF AM. GEOGRAPHERS 67, 70-71 (2000). "Close inspection by the research community has begun to illuminate the nuances of land-cover dynamics and to challenge the conventional wisdom on a number of fronts." NAT'L RESEARCH COUNCIL, *supra* note 7, at 50. For a discussion of some of the limitations of classifying vegetation zones from satellite data, see VEGETATION MAPPING FROM PATCH TO PLANET 321-28 (Roy Alexander & Andrew C. Millington eds., 2000).

14. Today's field biologist is likely to be carrying a laptop, cell phone, global positioning system, range finder and digital camera. Stein & Davis, *supra* note 5, at 21.

submersibles."[15] Genetic[16] and isotopic tracers[17] are increasingly being used to follow ecological processes in formerly inaccessible situations.[18] For example, the feeding patterns of wide-ranging raptors can now be better analyzed through the use of stable nitrogen isotope analyses of raptor pellets that indicate not only the nature of the raptor's prey but the kind of areas in which the prey were found.[19]

When these techniques are combined with satellite sensing and advanced systems for analyzing geographic information, they make it possible to identify key areas of ecological importance that humans may never have visited.[20] For example, a recent study that compared satellite data with ground-based sampling in remote parts of the Canadian arctic made it possible to map the diversity of plant species in the area with a high degree of accuracy and identify areas of high biodiversity despite the difficulty of obtaining ground access to much of the area.[21] And the ability to map the shallow subsurface of the land using new noninvasive techniques has provided accurate hydrological data never before available that

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15. NAT'L RESEARCH COUNCIL, *supra* note 7, at 25.

16. *See, e.g.*, Alexander Mosseler & O.P. Rajora, *Monitoring Population Viability in Declining Tree Species Using Indicators of Genetic Diversity and Reproductive Success, in* ENVIRONMENTAL FOREST SCIENCE : PROCEEDINGS OF THE IUFRO DIVISION 8 CONFERENCE ON ENVIRONMENTAL FOREST SCIENCE 333, 335-38 (Kyoji Sassa ed., 1998).

17. *See, e.g.*, Eric W. Wolff, *The Record of Aerosol Deposited Species in Ice Cores, and Problems of Interpretation, in* CHEMICAL EXCHANGE BETWEEN THE ATMOSPHERE AND POLAR SNOW 1-14 (Eric W. Wolff & Roger C. Bales eds., 1996) (describing use of tracers in study of Arctic ice cores); Jeffrey F. Kelly et al., *Insights into Wilson's Warbler migration from analyses of hydrogen stable-isotope ratios,* 130 OECOLOGIA 216 (2002). *See generally* DAVID STEVEN SCHIMEL, THEORY AND APPLICATION OF TRACERS (1993).

18. *See* John N. Thompson et al., *Frontiers of Ecology*, 51 BIOSCIENCE 15 (2001). *See, e.g.*, Alves & Skôle, *supra* note 12 (comparing land use patterns in Amazonia over five years); D.R. Robinson et al., *Linking Breeding and Wintering Ranges of a Migratory Songbird Using Stable Isotopes,* 295 SCI. 1062 (2002) (migratory patterns of warbler species discerned through examination of feathers of wintering birds and comparing geographic patterns in breeding ground isotopic signatures).

19. Elaine K. Harding & Emiko Stevens, *Using Stable Isotopes to Assess Seasonal Patterns of Avian Predation Across a Terrestrial-Marine Landscape,* 129 OECOLOGIA 436 (2001); *See also* Jeffrey F. Kelley et al., *Insights into Wilson's Warbler Migration from Analyses of Hydrogen Stable-Isotope Ratios,* 130 OECOLOGIA 216 (2002). For other examples, see the case studies found in GENETICS, DEMOGRAPHY AND VIABILITY OF FRAGMENTED POPULATIONS (Andrew G. Young & Geoffrey M. Clarke eds., 2000).

20. The research projects of various federal agencies that are analyzing environmental change are summarized in SUBCOMMITTEE ON GLOBAL CHANGE RESEARCH OF THE COMMITTEE ON ENVIRONMENTAL AND NATURAL RESOURCES OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL, OUR CHANGING PLANET: THE FY 2002 U.S. GLOBAL CHANGE RESEARCH PROGRAM (2001).

21. William Gould, *Remote Sensing of Vegetation, Plant Species Richness, and Regional Biodiversity Hotspots,* 10 ECOLOGICAL APPLICATIONS 1861, 1862 (2000).

will make it possible to follow ecological processes that could otherwise only be estimated.[22]

3. International Networks

The Internet has fostered the creation of increasing numbers of international networks that interchange data relevant to ecological research.[23] For example, a Global Coral Reef Monitoring Network[24] has been established by the Intergovernmental Oceanographic Commission and other agencies.[25] Other examples include the International Geosphere-Biosphere Programme,[26] the Global Population Dynamics Database,[27] and the Millennium Ecosystem Assessment.[28]

The availability of networks such as these has made it possible for scientists all over the planet to participate in joint research and modeling projects that produce results far faster than ever before attempted.[29] The work of the Intergovernmental Panel on Climate Change, which has produced extensive reviews of global climate change at five year intervals using the work of over a thousand scientists, is the most prominent example of the research capabilities of international networks.[30]

Private conservation organizations are also using large-scale ecology in proposals for increased protection of natural areas that

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22. On the mapping of the subsurface, *see generally* NAT'L RESEARCH COUNCIL, SEEING INTO THE EARTH: NONINVASIVE CHARACTERIZATION OF THE SHALLOW SUBSURFACE FOR ENVIRONMENTAL AND ENGINEERING APPLICATIONS (2000).

23. International agreements have attempted to secure the rights of nations from which remote sensing data are obtained to have access to the data. *See* Charles Davies et al., *supra* note 7, at 1107-12 (1999).

24. *See* http://www.icriforum (last visited Sept. 27, 2001)

25. Clive Wilkinson & Bernard Salvat, *The Global Reef Monitoring Network: Reversing the Decline of the World's Reefs*, *in* CORAL REEFS: CHALLENGES AND OPPORTUNITIES FOR SUSTAINABLE MANAGEMENT 16, 17-18 (Marea E. Hatziolos et al., eds. 1997).

26. *See* http://www.igbp.kva.se (last visited Mar. 7, 2002). The first report of the IGBP was PLANT FUNCTIONAL TYPES: THEIR RELEVANCE TO ECOSYSTEM PROPERTIES AND GLOBAL CHANGE (T.M. Smith et al. eds., 1997).

27. *See* http://www.cpb.bio.ic.ac.uk (last visited Mar. 7, 2002). *See* Pablo Inchausti & John Halley, *Investigating Long-Term Ecological Variability Using the Global Population Dynamics Database*, 293 SCI. 655 (2001).

28. The United Nations began this program in 2001. *See* http://www.millenniumassessment.org (last visited Mar. 7, 2002). For other United Nations global environmental programs, *see* http://www.unep.org/Geo2000/ (last visited Mar. 7, 2002).

29. For a discussion of a number of European-based networks, see David L. Hawksworth, *The Response of the International Scientific Community to the Challenge of Biodiversity*, *in* NATURE AND HUMAN SOCIETY: THE QUEST FOR A SUSTAINABLE WORLD 347, 347-54 (Peter H. Raven ed., 2000).

30. *See* http://www.ipcc.ch (last visited Mar. 7, 2002). For a detailed review of the IPCC's work as applied to the United States, see NAT'L ASSESSMENT SYNTHESIS TEAM, UNITED STATES GLOBAL CHANGE RESEARCH PROGRAM, CLIMATE CHANGE IMPACTS ON THE UNITED STATES: THE POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE (2001).

extend beyond national borders. The Yellowstone-to Yukon initiative, which seeks to develop wildlife corridors extending through the northern Rocky Mountains and Canada, is a privately-initiated effort that has attracted a great deal of attention and support.[31] Along the border between the United States and Mexico, the Sonoran Institute has been working with Native American tribes and Mexican conservation organizations to develop integrated means of addressing ecological issues in the Sonoran desert and the Colorado River delta.[32] And a privately funded effort has begun an ambitious project called Species 2000 that hopes to inventory the world's 1.75 million known species.[33]

4. Analytical Capacity

Analytic methods are also improving,[34] and rapidly growing computer capacity enables the processing of increasing quantities of information each year.[35] A panel of the National Research Council recently pointed out that advances are continuing to be made toward solving some major methodological problems involved in the analysis of spatial data.[36] Only recently has information technology enabled us to analyze data on such large scales[37] and to

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31. *See* http://www.rockies.ca/y2y/ (last visited Mar. 7, 2002).

32. Jeffrey P. Cohn, *Delta in a Delicate Balance*, AMÉRICAS, October 2001, at 36. *See* C. Luther Propst & Peter W. Culp, *Searching for Cibola: Community-based Environmental Restoration in the Colorado River Watershed*, 42 ARIZ. L. REV. 259 (2000); William Snape III et al., *Protecting Ecosystems Under the Endangered Species Act: The Sonoran Desert Example*, 41 WASHBURN L.J. 14, 28-36, 45-49 (2001). For further information on the Sonoran Institute's work in Mexico, see http://www.sonoran.org/garden/isda.html (last visited Oct. 4, 2001).

33. Andrew Lawler, *Up for the Count?*, 294 SCI. 769 (2001).

34.

> Remote imagery has provided new access to spatial data. Geographic Information Systems (GIS) have facilitated the handling, analysis and display of spatial data. New theory has provided the means to quantify pattern, test hypotheses against random expectations, and come to grips with complexity and scale. The stage seems set for breakthroughs in the new millennium. (Citations omitted).

R.V. O'Neill, *Theory in Landscape Ecology*, *in* ISSUES IN LANDSCAPE ECOLOGY 1 (John A. Wiens & Michael R. Moss eds., 1999). *See also* BRIAN A. MAURER, GEOGRAPHICAL POPULATION ANALYSIS: TOOLS FOR THE ANALYSIS OF BIODIVERSITY (1994).

35. *See, e.g.*, John Gordon & Jane Coppock, *Ecosystem Management and Economic Development*, *in* THINKING ECOLOGICALLY: THE NEXT GENERATION OF ENVIRONMENTAL POLICY 37, 40 (Marian R. Chertow & Daniel C. Esty eds., 1997) (stating that computational advances allow environmental managers to consider a much wider range of variables than was possible even just a few years ago).

36. NAT'L RESEARCH COUNCIL, *supra* note 7, at 52.

37. R.S. Defries & J.R.G. Townshend, *Global Land Cover Characterization from Satellite Data: From Research to Operational Implementation*, 8 GLOBAL ECOLOGY AND BIOGEOGRAPHY 367 (1999).

compare the way that the data change over time.[38] Such comparisons have strengthened our awareness of the dynamic character of ecological systems.[39] For example, the combination of powerful analytical methods and new techniques of tracing genetic material makes it possible to map the spatial distribution of genealogical lineages of organisms and deduce their past movements.[40]

These capabilities are beginning to spread beyond the institutions of the developed countries.[41] There has been a continuing increase in the availability of large scale ecological information in the Southern hemisphere, which was formerly sparse.[42] For example, a recent paper compared and analyzed the geographic ranges of almost three thousand South American birds, identifying the ecological characteristics that were typical of the habitats of those species that were declining in number.[43] And remote sensing is now being used to trace the conditions in which the bacteria that causes cholera is present in the coastal waters of the Bay of Bengal.[44] The importance of the El Niño phenomenon to the ecology and the economies of Southern hemisphere countries has provided a major incentive for further strengthening the scientific capabilities of many of those countries.[45]

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38. STAN MORAIN, GIS SOLUTIONS IN NATURAL RESOURCE MANAGEMENT: BALANCING THE TECHNICAL-POLITICAL EQUATION 307 (1999) (Only recently has it been possible to integrate GIS data into temporal dynamic models successfully); *see, e.g.*, Cecile Cabanes et al., *Sea Level Rise During Past 40 Years Determined from Satellite and in Situ Observations*, 294 SCI. 840 (2001).

39. "A consequence of working at large spatial and temporal scales is a tendency to be impressed by how spatially variable and ephemeral ecological communities are." STEPHEN P. HUBBELL, THE UNIFIED NEUTRAL THEORY OF BIODIVERSITY AND BIOGEOGRAPHY 21 (2001). An understanding of the long-term dynamics of ecosystems is extremely useful to natural resource managers. Jacqueline Lesley Brown, *Preserving Species: The Endangered Species Act Versus Ecosystem Management Regime, Ecological and Political Considerations, and Recommendations for Reform*, 12 J. ENVTL. L. & LITIG. 151, 237-41 (1997).

40. *See* J.C. Avise, *The History and Purview of Phylogeography*, 7 MOLECULAR ECOLOGY 371 (1998).

41. Stuart l. Pimm et al., *Can We Defy Nature's End?*, 293 SCI. 2207, 2208 (2001).

42. Robert M. May, *Conceptual Aspects of the Quantification of the Extent of Biological Diversity*, *in* BIODIVERSITY: MEASUREMENT AND ESTIMATION 13, 18-19 (D.L. Hawksworth ed., 1995).

43. Carsten Rahbek & Gary R. Graves, *Multiscale assessment of patterns of avian species richness*, 98 PROC. NAT'L ACAD. SCI. U.S.A. 4534 (2001) (study using database showing geographic ranges of 2,869 species of birds breeding in South America). For commentary on this and similar studies, see Katherine J. Willis & Robert J. Whittaker, *Species Diversity – Scale Matters*, 295 SCI. 1245 (2002), *available in an enhanced version at* www.sciencemag.org/cgi/content/full/295/5558/1245.

44. Brad Lobitz et al., *Climate and infectious disease: Use of remote sensing for detection of Vibrio cholerae by indirect measurement*, 97 PROC. NAT'L. ACAD. SCI. USA 1438 (2000).

45. *See, e.g.*, Milena Holmgren et al., *El Niño Effects on the Dynamics of Terrestrial Ecosystems*, TRENDS IN ECOLOGY AND EVOLUTION, Feb. 2001, at 89. *See generally* ADVANCES IN HISTORICAL ECOLOGY (William Balée ed., 1998).

B. Temporal Scale

Technology has expanded the ability to study the natural world both backward and forward in time. This enables ecologists to study the past and forecast the future in ways that were impossible a few decades ago.[46]

1. Paleoecology

The current composition, structure and function of an ecological system are, in part, a consequence of events that took place centuries ago.[47] From the beginning, ecologists recognized the importance of linking ecology, geology, and paleontology.[48] Studies of peat bogs provided evidence of layers of different types of vegetation laid down in presumed time series.[49] By the 1920s, ecologists were identifying pollen grains preserved in peat and sediment deposits.[50]

By the 1970s, carbon-14 analysis became a common method of dating specimens, and new techniques of pollen analysis enabled ecologists to operate in all kinds of soils and climates.[51] While earlier ecologists were restricted to snapshots of recent conditions, today the technology for reconstructing ecologies of the distant past make it possible to view the history of the natural world from long-range time perspectives.[52] Paleoecology, as the study of prehistoric ecological conditions is called, has become an important field in its own right.[53]

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46. *See generally Ecology Through Time*, 293 SCI. 623-60 (July 27, 2001),*available at* http://www.sciencemag.org/feature/data/ecology2001.shtml (last visited Mar. 7, 2001).

47. V.H. Dale et al., *Ecological Principles and Guidelines for Managing the Use of Land*, 10 ECOLOGICAL APPLICATIONS 639, 649 (2000).

48. *See generally* James C. Ritchie, *Paleoecology: Status and Prospect, in* QUARTERNARY LANDSCAPES 113 (Linda C.K. Shane & Edward J. Cushing eds., 1991).

49. Thompson Webb III, *Paleoecology, in* 4 ENCYCLOPEDIA OF BIODIVERSITY 451, 457-58 (Simon A. Levin ed., 2001) (time range of sediment cores from lakes or bogs can range from 50 years to millions of years).

50. ROBERT P. MCINTOSH, THE BACKGROUND OF ECOLOGY: CONCEPT AND THEORY 98-104 (1985).

51. *Id.* at 102-04.

52. *See, e.g.*, Mark T. Clementz & Paul L. Koch, *Differentiating Aquatic Mammal Habitat and Foraging Ecology with Stable Isotopes in Tooth Enamel*, 129 OECOLOGIA 461 (2001) (explaining the stable isotope analysis of the tooth enamel of museum specimens can offer insight into the ecology of extinct animals that lived millions of years ago). *See generally* JAMES H. BROWN, MACROECOLOGY 189-91 (1995). For a series of papers oriented toward the research necessary to find evidence for the practice of ecosystem restoration, see THE HISTORICAL ECOLOGY HANDBOOK: A RESTORATIONIST'S GUIDE TO REFERENCE ECOSYSTEMS (David Egan & Evelyn A. Howell eds., 2001).

53. M. TOKESHI, SPECIES COEXISTENCE: ECOLOGICAL AND EVOLUTIONARY PERSPECTIVES 9-11 (1999).

Paleoecological methodology has increased in sophistication in recent years.[54] Analysis of pollen[55] from ancient lake sediments,[56] marine sediments,[57] or ice fields[58] and studies of fossil DNA[59] are examples of scientific methods that were unknown until recently. These methods have been particularly helpful in tracing past climate changes. Fine-resolution sampling of records from ocean sediments, lakes, and ice cores has revealed sudden shifts of climate occurring within years or decades at many different times in the past, suggesting that the climate system can shift much more rapidly than previously assumed.[60] For example, a recent study of coastal ecosystems analyzed data from marine sediments going back about 125,000 years.[61]

2. Long-Term Ecological Records

Although systematic record-keeping for the purpose of ecological research began only in the twentieth century,[62] the passage of time each year gives scientists additional historical records from sources such as accurate wildlife surveys and weather and climate data.[63] As time passes, the trends in such data become more reliable,

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54. For example, chemical analyses of fluids trapped in tiny rocks spaces are being used to reconstruct past climates. Robert H. Goldstein, *Clues from Fluid Inclusions*, 294 SCI. 1009 (2001).

55. Interpretation of pollen data involves establishing the composition of the vegetation that delivered the pollen, and then inferring the climate, ecology and perhaps the human activities that would have generated that mix of vegetation. KNUT FAEGRI & JOHS. IVERSEN, TEXTBOOK OF POLLEN ANALYSIS 115-16 (4th ed., 1989).

56. John P. Smol, *Paleoecology: A Diagnostic Approach to Assessing Ecosystem Health*, *in* ECOSYSTEM HEALTH 210, 210 (David Rapport et al. eds., 1998) (explaining the study of lake histories from sediment profiles is known as paleolimnology).

57. *See, e.g.*, Richard B. Aronson & William F. Precht, *Stasis, Biological Disturbance and Community Structure of a Holocene Coral Reef*, 23 PALEOBIOLOGY 326 (1997) (analyzing the core data showed that recently declining reef species had been dominant for at least 3800 years).

58. *See, e.g.*, Gina E. Hannon et al., *6000 Years of Forest Dynamics in Suserup Skov, a Seminatural Danish Woodland*, 9 GLOBAL ECOLOGY & BIOGEOGRAPHY 101 (2000). ROBERT E. RICKLEFS, THE ECONOMY OF NATURE 579-80 (4th ed., 1996).

59. Laura F. Landweber, *Something Old for Something New: The Future of Ancient DNA in Conservation Biology*, *in* GENETICS AND THE EXTINCTION OF SPECIES 163 (Laura F. Landweber & Andrew P. Dobson eds., 1999).

60. NAT'L RESEARCH COUNCIL, *supra* note 7, at 28-29.

61. Jeremy B.C. Jackson et al., *Historical Overfishing and the Recent Collapse of Coastal Ecosystems*, 293 SCI. 629 (2001).

62. Andrew Sugden & Richard Stone, *Filling Generation Gaps*, 293 SCI. 623 (2001).

63. *See, e.g.*, Jennifer M. Parody et al., *The Effect of 50 Years of Landscape Change on Species Richness and Community Composition*, 10 GLOBAL ECOLOGY & BIOGEOGRAPHY 305 (2001) (comparing 50 years of data on bird observations and land cover for an area of northern lower Michigan); Jason Jones et al., *Assessing the Effects of Natural Disturbance on a Neotropical Migrant Songbird*, 82 ECOLOGY 2628 (2001) (analyzing effect of severe Quebec ice storm on populations of warblers that were being studied).

leading to the reevaluation of many earlier assumptions.[64] For example, analysis of such records has made ecologists aware that evolution of organisms takes place more rapidly than had traditionally been assumed[65] and has cast new light on the influence of climate change.[66]

The National Science Foundation sponsors a series of sites on which a wide variety of ecological information is being maintained over the long term. This Long Term Ecological Research network is the largest single project in ecological research, involving over 1200 scientists and students working on 24 different sites.[67] Other long term data sets of importance to ecological science are being developed by NOAA's Climate Monitoring and Diagnostics Laboratory, the National Aeronautical and Space Administration, the Environmental Protection Agency, and the Department of Energy's Carbon Dioxide Information and Analysis Center.[68]

3. Mining Historical Records

In addition, ecologists have found ways of deriving ecological information from historical records maintained for other purposes, enabling them to reconstruct time series for many species of organisms dating back well into the nineteenth century.[69] A wide variety of organizations have been keeping censuses of particular types of animals for long periods of time.[70] A consortium of universities has assembled a Global Population Dynamics Database that contains more than 4500 time series of population abundance for over 1800 animal species across many geographical locations.[71]

64. Jocelyn Kaiser, *An Experiment for All Seasons*, 293 SCI. 624 (2001).

65. John N. Thompson, *Rapid Evolution as an Ecological Process*, 13 TRENDS IN ECOLOGY AND EVOLUTION 329 (1998). *See also* Craig Packer et al., *Egalitarianism in Female African Lions*, 293 SCI. 690 (2001).

66. James H. Brown et al., *Complex Species Interactions and the Dynamics of Ecological Systems: Long-Term Experiments*, 293 SCI. 643, 648-49 (2001). For a readable discussion of one biologist's long term ecological experiment and its relationship to climate change, see Darcy Frey, *George Divoky's Planet*, N.Y. TIMES MAG., Jan. 6, 2002, at 24.

67. Kaiser, *supra* note 64, at 624.

68. NAT'L RESEARCH COUNCIL, *supra* note 7, at 18.

69. Sugden & Stone, *supra* note 62, at 623.

70. For example, the National Audubon Society has records of Christmas bird counts for over a century. The first Christmas Bird Counts (CBCs) were conducted in 1900 in response to a suggestion made in the National Audubon Society's magazine, and the survey has been coordinated by the National Audubon Society ever since and has become the oldest continuous wildlife survey in North America. *See* http://www.mp1-pwrc.usgs.gov/birds/cbc.html (last visited Sept. 17, 2001). Because of the popularity of birds, historical data on their breeding and movements is better than for other animals. Stein & Davis, *supra* note 5, at 38.

71. Pablo Inchausti & John Halley, *Investigating Long-Term Ecological Variability Using the Global Population Dynamics Database*, 293 SCI. 655 (2001).

The database contains records of the prevalence of 544 series of animal species for periods of thirty years or more.[72] Museum specimens collected at various times in the past also provide opportunities to trace changes in the genetic makeup of organisms over time.[73]

In addition, ecologists are finding old ecological information in surprising locations. For example, one recent research project analyzed the use of "witness-trees" in early American surveys to describe presettlement forest vegetation.[74] A European study examined old pictures on postcards to trace the history of vegetation changes in particular areas.[75] Another project examined New England newspapers and other records dating back to the 17th century to determine the timing and ecological impact of hurricanes that had hit New England.[76]

4. Phylogenetics

Moreover, new molecular biology techniques make it possible to reconstruct the ways in which organisms evolved, throwing new light on some traditional taxonomies.[77] A panel of the National Research Council reported that:

> Genomics using polymerase chain reaction (PCR) and microarrays can now be used for rapidly and efficiently assessing genotypic diversity and variation in gene expression. Molecular tools for characterizing microbial diversity reveal vast stores of hidden diversity in oceans, sediments, and soils, including environments at extremes of temperature and pressure. These methods will lead to new insights into the significance and consequences of

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72. *Id.* at 656. The database is continually updated and can be accessed at http://www.cpb.bio.ic.ac.uk (last visited Sept. 6, 2001).

73. *See, e.g.*, Marie L. Hale et al., *Impact of Landscape Management on the Genetic Structure of Red Squirrel Populations*, 293 SCI. 2246 (2001) (DNA tests on museum specimens of various ages show how increasing forest connectivity over time improved gene flow through metapopulation).

74. Bryan A. Black & Marc D. Abrams, *Influences of Native American and Surveyor Biases on Metes and Bounds Witness-Tree Distribution*, 82 ECOLOGY 2574 (2001).

75. Max Debussche et al., *Mediterranean Landscape Changes: Evidence From Old Postcards*, 8 GLOBAL ECOLOGY & BIOGEOGRAPHY 3 (1999).

76. Emery R. Boose et al., *Landscape and Regional Impacts of Hurricanes in New England*, 71 ECOLOGICAL MONOGRAPHS 27, 30 (2001).

77. *See, e.g.*, James E. Richardson et al., *Rapid and Recent Origin of Species Richness in the Cape Flora of South Africa*, 412 NATURE 181 (2001) (using DNA sequence data to determine that the wide variety of species in the Cape region resulted from relatively recent speciation).

diversity below the species level, as well as better understanding of species diversity.[78]

As one group of biologists recently put it, "The luxury of now having more basic natural history data across taxa, at the same time that our reconstructions of phylogenetic history are precise and reliable, almost gives optimism for countering daily extinction rates."[79]

5. Modeling the Future

The time scales needed to analyze ecological functions vary greatly.[80] Increased computer modeling power enables ecologists to project future conditions at whatever time scale is needed to capture the rate of change of a particular ecological process,[81] which may range from "minutes to millennia."[82] Modern computer models enable ecologists to project future conditions at any of these time scales, and while the complexity of ecological systems makes the predictive value of many such models somewhat speculative,[83] the modeling allows scientists to think in expanded ways that were not feasible for an earlier generation.[84] For example, the National Park Service and the United States Geological Survey study a Regional Hydro-Ecological Simulation System to evaluate future resource

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78. NAT'L RESEARCH COUNCIL, *supra* note 7, at 25.

79. J.L. Gittleman et al., *Detecting ecological pattern in phylogenies, in* BIODIVERSITY DYNAMICS: TURNOVER OF POPULATIONS, TAXA, AND COMMUNITIES 51, 64-65 (Michael L. McKinney & James A. Drake eds., 1998).

80. "Rates of carbon uptake and water loss through stomata can be measured and are expressed in seconds; growth, however, is measured in days to weeks; and life history characteristics in generations that can take place in periods of a year or less or may take tens and even hundreds of years." O.T. Solbrig, *Plant Traits and Adaptive Strategies: Their Role in Ecosystem Function, in* BIODIVERSITY AND ECOSYSTEM FUNCTION 97, 107 (Ernst-Detlef Schulze & Harold A. Mooney eds., 1994).

81. James S. Clark et al., *Ecological Forecasts: An Emerging Imperative,* 293 SCI. 657 (2001).

82. For example, in a grassland the time scales of key ecological processes are: (1) precipitation: minutes to hours; (2) transpiration: hours to days; (3) forage production: days to months; (4) species composition changes: months to years; (5) soil formation: years to centuries; (6) geomorphic change: centuries to millennia. Paul G. Risser, *Landscape Ecology: State of the Art, in* LANDSCAPE HETEROGENEITY AND DISTURBANCE 3, 10 (Monica Goigel Turner ed., 1987)

83. NAT'L RESEARCH COUNCIL, *supra* note 7, at 23 (dynamic global vegetation models attempt to simulate habitat distribution based on competition among the major functional types of plants, but our limited understanding of the factors that control such competition make the results tentative). *See* MICHAEL J. G. VAN EETEN & EMERY ROE, ECOLOGY, ENGINEERING AND MANAGEMENT 75-77 (2002) (ecological models have many problems but are steadily improving).

84. *Id.* at 57.

conditions in Glacier National Park under various climate scenarios.[85]

C. A Greater Vision

Current research in large-scale ecology offers interesting lessons that should be useful in fashioning the environmental laws of the twenty-first century.[86] The greater vision scientists have obtained through large scale ecology[87] has turned some earlier ideas that much of the public thought were "eternal truths" into variables, which apply only under certain time and space conditions. First, the old cliché "the survival of the fittest" is not going to leave us with a world populated solely by cockroaches and rats. Competition, in combination with evolution and environmental change, should produce some increases in biodiversity. But in some cases, particularly on islands, competition from invasive species can be both an ecological and economic hazard.[88]

Second, the assumption that "fragmentation of habitat" is always evil is unsound. In many situations, a mosaic of small patches of differing habitats provides ecological processes that are essential to the survival of many types of organisms. There are some situations, particularly where there are large blocks of forest, where the destruction of the forest at current rates threatens the collapse of ecological systems and the loss of diversity, but the threat is from the scale of habitat destruction far more than from the process of fragmentation.[89]

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85. Daniel B. Fagre, *Understanding Climate Change Effects on Glacier National Park's Natural Resources*, *in* U.S. GEOLOGICAL SURVEY, STATUS AND TRENDS OF THE NATION'S BIOLOGICAL RESOURCES, *at* http://biology.usgs.gov/s+t/SNT/noframe/c1111.htm (last visited Dec. 4, 2001).

86. *See generally* Jacqueline Lesley Brown, *Preserving Species: The Endangered Species Act Versus Ecosystem Management Regime, Ecological and Political Considerations, and Recommendations for Reform*, 12 J. ENVTL. L. & LITIG. 151, 237-41 (1997). Advances in large scale ecology affect conservation organizations as well as government agencies. For example, the Nature Conservancy says that a "new appreciation of the importance of broad-scale ecological and evolutionary processes to conservation gives new impetus to increasing the geographic and temporal scale of our conservation efforts." Jonathan S. Adams et al., *Biodiversity: Our Precious Heritage*, *in* PRECIOUS HERITAGE: THE STATUS OF BIODIVERSITY IN THE UNITED STATES 3, 16 (Bruce A. Stein et al. eds., 2000).

87. The *increase* in scale is not the only important advance in ecological science. Small-scale ecology is also unveiling new vistas. Molecular biology and microbiology have opened up new frontiers of knowledge–including an increased awareness of the mutualistic or symbiotic relationship of many forms of life–but that is the not within the scope of this article. For a recent and readable analysis of some of this research, see TOM WAKEFORD, LIAISONS OF LIFE (2001).

88. *See infra* Section III.A.

89. *See infra* Section III.B.

Third, the concept of "natural disaster" needs to be reevaluated. Many disturbances are natural processes that have played important roles over time in maintaining cycles of environmental release and renewal. Seen from a large spatio-temporal perspective, many of the patterns of change in the natural environment seem to be more cyclical than previously realized.[90] These cycles include "disturbance" phases that we have previously characterized as natural disasters such as fire, flood, and pest outbreak. Some changes in the landscape that we thought were irreversible may actually be inevitable and useful parts of the natural cycle of change.[91] As long as the disturbance can be kept within historical parameters, ecological systems can adjust to storms, fire, disease, and other disturbance. But when humans cause disturbance outside the framework of historical precedent, the results are unpredictable.[92]

This leads, finally, to the conclusion that if humans can keep their alteration of nature within parameters that ecological systems have experienced in the past, the systems are likely to retain existing ecological functions over broad scales of time and place. The key question is whether scientists can identify the limits beyond which we risk ecological collapse, and whether we can develop laws and policies that will keep us within those limits.[93]

In essence, this means that we need to be able to tell the difference between (1) human activities that merely imitate cyclical changes to which ecological systems are prepared to adapt, and (2) human activities that cause linear, unidirectional, continuous change that takes us into realms beyond the experience of ecological systems.[94] I am optimistic that the rapid pace of ecological research will increasingly be able to draw that metastability line, but I am less sanguine about our ability to keep ourselves from crossing it.

Armed with this scientific knowledge, resource managers are trying to rethink their management techniques to better cope with these cycles. We can hope to cope with cyclical changes in the natural world through a better understanding of ecological processes. But some of the changes humans are causing seem to be

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90. ROBERT M. MAY, *Introduction to the Princeton Landmarks in Biology Edition, xi, xiv-xvii*, STABILITY AND COMPLEXITY IN MODEL ECOSYSTEMS (2001) (long runs of time-series data needed to sort out cyclical ecological patterns from chaotic patterns). *See, e.g.*, J.E. Hewitt et al., *Assessing environmental impacts: Effects of spatial and temporal variability at likely impact scales*, 11 ECOLOGICAL APPLICATIONS 1502 (2001) (noting difficulty of assessing impact under conditions of spatial and temporal variability).

91. SIMON A. LEVIN, FRAGILE DOMINION: COMPLEXITY AND THE COMMONS 114-15 (1999).

92. *See infra* Section III.C.

93. *See infra* Section III.D.

94. *See infra* text accompanying notes 432-46.

unidirectional rather than cyclical. The rate of increase of nitrogen in the water[95] and carbon dioxide in the air,[96] for example, seem to be steady and inexorable. The first generation of environmental laws sought to ameliorate human activities that were making highly visible changes in the natural environment that seemed irreversible. Today, however, the gradual, insidious and seemingly inexorable change caused by human activities such as nitrogen deposition and greenhouse gas emission are among the most serious problems. Unless we can counteract such trends, we may be venturing into areas beyond the ability of science to foresee the effect on the natural world.[97]

Section II of this article will summarize some of the theoretical premises on which large scale ecology is based. Section III will review some of the most interesting results of current research in large-scale ecology. Section IV will suggest some ways in which the results of this research could usefully be applied by lawmakers.

II. PREMISES OF LARGE-SCALE ECOLOGY

The term "ecology" appears so loosely[98] in general usage that the public sometimes tends to overlook the fact that ecology is a specific field of study within the biological sciences. Ecologists tend to subdivide their field by level of organization; ecologists' subdisciplines focus on individual organisms, populations, communities, ecosystems, or landscapes.[99] A landscape is a cluster or "mosaic" of interacting ecological systems,[100] and the branch of ecology known as "landscape ecology" studies the ecological effects of this patterning.[101] Ecologists, like all scientists, have their

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95. *See infra* text accompanying notes 492-512.

96. *See infra* text accompanying notes 457-89.

97. *See infra* text accompanying notes 531-59.

98. The popular media often use "ecology" to refer to anything that smells vaguely green to them. And radical ideologues have coined the term "deep ecology" as the name for a political movement that seeks to eliminate anthropocentric behavior. *See* ARRAN E. GARE, POSTMODERNISM AND THE ENVIRONMENTAL CRISIS 86-96 (1995); *see generally* DEEP ECOLOGY (Michael Tobias ed., 1985).

99. Richard J. Hobbs, *Managing Ecological Systems and Processes*, *in* ECOLOGICAL SCALE: THEORY AND APPLICATIONS 459, 464-65 (David L. Peterson & V. Thomas Parker eds. 1998) (defining terms).

100. Anthony W. King, *Hierarchy Theory: A Guide to System Structure for Wildlife Biologists*, *in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 185, 205-06 (John A. Bissonette ed., 1997).

101. For a concise summary of the scope of current landscape ecology, see Steward T.A. Pickett and M. L. Cadenasso, *Landscape Ecology: Spatial Heterogeneity in Ecological Systems*, 269 SCI. 331 (1995). *See also* David W. Burnett, *New Science but Old Laws: The Need to Include Landscape Ecology in the Legal Framework of Biodiversity Protection*, 23 ENVIRONS ENVTL. L. & POL'Y J. 47 (Fall 1999).

internal disagreements, and some prefer the term "macroecology"[102] over "landscape ecology," and still others treat all large-scale ecology within the definition of "ecosystem ecology."[103] I will use the general term "large-scale" to describe ecological research at scales larger than those typically used in population ecology or community ecology. "Large-scale ecology" is a descriptive term that does not seem to carry any academic jurisdictional baggage.[104]

A number of hypotheses have arisen out of, or been strongly influenced by, the study of ecological processes at large-scales. Some of these have developed a strong body of influential support. In this part of the article I will describe those that seem to have the most relevance to the development of law and policy.

A. Ecosystems are Human-Generated Concepts

Ecological science has used today's technology for processing large amounts of information to put together visions of the natural world at a much larger scale than was previously possible. Although ecology still gains many insights from analysis of small-scale phenomena, large-scale ecology is beginning to make us realize that ecological systems are more than just the sum of their parts.[105] Large-scale ecology gives us a view of the world in which the concept of the "ecosystem," which dominated the vocabulary of popular environmentalism for decades,[106] is giving way to more nuanced ideas.[107]

Ecologists now recognize that each of the rules that govern the ecological processes operates at its own scale. We cannot arbitrarily select any boundary for an ecosystem in space and time nor assume that the rules for that ecosystem operate within, and only within,

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102. BROWN, *supra* note 52; KEVIN J. GASTON & TIM M. BLACKBURN, PATTERN AND PROCESS IN MACROECOLOGY (2000); BRIAN A. MAURER, UNTANGLING ECOLOGICAL COMPLEXITY: THE MACROSCOPIC PERSPECTIVE (1999). Macroecologists try to bring together such separate disciplines as systematics, ecosystem ecology, paleontology, and community ecology. Brian A. Maurer, *Macroecology and Consilience*, 9 GLOBAL ECOLOGY & BIOGEOGRAPHY 275 (2000).

103. For concise definitions of the various branches of landscape ecology, see John A. Wiens, *Metapopulation Dynamics and Landscape Ecology*, *in* METAPOPULATION BIOLOGY: ECOLOGY, GENETICS AND EVOLUTION 43, 45 (Ilkka Hanski & Michael E. Gilpin eds., 1997).

104. *See* Robert M. May, *The Effects of Spatial Scale on Ecological Questions and Answers*, *in* LARGE-SCALE ECOLOGY AND CONSERVATION BIOLOGY 1 (P.J. Edwards et al. eds., 1993). Not all of the ecologists whom I have cited in support of these propositions would necessarily label themselves as "large-scale" ecologists, but the boundaries of the subspecialties of ecology are notoriously fuzzy.

105. LEVIN, *supra* note 91, at 17-38.

106. FRANK BENJAMIN GOLLEY, A HISTORY OF THE ECOSYSTEM CONCEPT IN ECOLOGY, 117-18, 175-76 (1993).

107. S.T.A. Pickett & M.L. Cadenasso, *The Ecosystem as a Multidimensional Concept: Meaning, Model, and Metaphor*, 5 ECOSYSTEMS 1 (2002); Stein & Davis, *supra* note 5, at 47-49 (there is no consensus on any single method for mapping ecological communities).

that boundary.[108] Ecological topology, as some scientists call it, is more complex than that, which makes its study challenging, but also makes it more realistic.[109] In other words, we need not define ecosystem the same way for the warbler and the eagle.[110]

For example, in the central United States we have begun to refer to areas of mixed trees and grassland as "savannas," a type of habitat that had not been thought to exist in the area until recently.[111] Should we call this type of habitat an ecosystem, or should we call it an "ecotone" – the term used to describe the boundary between two ecosystems?[112] What may appear as a relatively discrete boundary at one scale may look more like a continuous gradient at finer levels of resolution.[113] Does it really matter, unless we arbitrarily choose to target only something we legally define as an "ecosystem" for analysis and protection?[114]

1. Ecological Systems Are Open to Outside Influences

Contemporary ecologists assume that ecosystems are *open* – in other words, that they are susceptible to outside influences.[115] Most early ecological studies assumed that the ecological systems

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108. DAN R. PERLMAN & GLENN ADELSON, BIODIVERSITY: EXPLORING VALUES AND PRIORITIES IN CONSERVATION 105 (1997) ("the geographic landscape contains no unambiguous boundaries.").

109. Thompson et al., *supra* note 18.

110. John A. Wiens, *Habitat Fragmentation: Island v. Landscape Perspectives on Bird Conservation*, 137 IBIS S97, S98 (1994). *See* Risser, *supra* note 82, at 8-9 ("Each species views the landscape differently, and what appears as homogeneous patch to one may comprise a very heterogeneous patchy environment to another); ALMO FARINA, LANDSCAPE ECOLOGY IN ACTION 16-19 (2000) (animals perceive landscape through fixed genetic cues and accumulated experience).

111. WILLIAM K. STEVENS, MIRACLE UNDER THE OAKS 87-91 (1995). Although most ecologists reserve the use of the term ecosystem to a particular parcel of land, the term is often popularly applied to the characteristics of particular types of land, such as "wetland ecosystems." PERLMAN & ADELSON, *supra* note 108, at 111-14.

112. John B. Taft, *Savanna and Open-Woodland Communities*, *in* CONSERVATION IN HIGHLY FRAGMENTED LANDSCAPES 24 (Mark W. Schwartz ed., 1997). Some biologists are uncomfortable with the term "habitat" as well, probably because it originated in relation to hunting and fishing laws that failed to take into account non-game species. *See* JAMES F. BERRY & MARK S. DENNISON, THE ENVIRONMENTAL LAW AND COMPLIANCE HANDBOOK 669-70 (2000).

113. Jerzy Solon, *Integrating Ecological and Geographical (Biophysical) Principles in Studies of Landscape Systems*, *in* ISSUES IN LANDSCAPE ECOLOGY 22, 23 (John A. Wiens & Michael R. Moss eds., 1999).

114. *See* Robert V. O'Neill, *Is It Time to Bury the Ecosystem Concept? (With Full Military Honors, of Course!)*, 82 ECOLOGY 3275 (2001).

115. "Ecosystems are open to flows of energy, elements, and biota." Judy L. Meyer, *Conserving Ecosystem Function*, *in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 136, 138 (Steward Pickett et al. eds., 1997). *See also* V. Thomas Parker & S.T.A. Pickett, *Restoration as an Ecosystem Process: Implications of the Modern Ecological Paradigm*, *in* RESTORATION ECOLOGY AND SUSTAINABLE DEVELOPMENT 17, 22 (Krystyna M. Urbanska et al. eds., 1997).

analyzed had a relatively uniform structure and that the processes that created the structure were relatively uniform in space; thus they could treat each ecosystem as a closed and self-sufficient system.[116] Today we recognize that "neither boundaries on maps nor fences in the real world hold back" outside influences on ecological systems.[117]

Earlier ecologists often hoped to find that ecosystems had natural boundaries, but today's ecologists recognize that all ecological systems are somewhat flexible artifacts that we define for purpose of facilitating the study and management of natural areas.[118] Ecosystems must be defined in terms of their "scale," i.e., their location in space and time.[119] Large scale ecologists study the interrelationships between the biotic structure of an ecological system as well as its physical environment and setting within the landscape.[120] From that vantage point, the description of the boundaries of a particular ecosystem may seem quite arbitrary since it is apparent that all of the ecosystems are interrelated.[121]

2. Ecological Systems Are Complex

The various elements of ecological systems are interrelated in complex ways and the degree of complexity is increasing over time.[122] The structural complexity of ecological systems is closely

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116. Steward T.A. Pickett & Kevin H. Rogers, *Patch Dynamics: The Transformation of Landscape Structure and Function*, *in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 101, 102 (John A. Bissonette ed., 1997). The famous early twentieth-century ecologist Frederic Clements believed that science could identify ecological units that had the properties of organisms, a theory that has since fallen into disrepute but may have influenced the development of the idea that ecosystems had fixed boundaries defined by nature rather than by the human analyst. Giulio A. De Leo & Simon Levin, *The Multifaceted Aspects of Ecosystem Integrity*, 1 CONSERVATION ECOLOGY (1997), *available at* http://www.consecol.org/vol1/iss1/art3.

117. Pickett & Rogers, *supra* note 116, at 119. *See also* Solon, *supra* note 113, at 24 (each organism defines a mosaic of habitat or resource patches differently and on different scales).

118. The concept of an ecological community is threatening to become "an idea as likely to generate confusion as enlightenment." L.B. Slobodkin, *Limits to Biodiversity (Species Packing)*, *in* 3 ENCYCLOPEDIA OF BIODIVERSITY 729, 735 (Simon Asher Levin ed., 2001).

119. For a categorization of the various approaches to scale used by ecologists, see David L. Peterson & V. Thomas Parker, *Dimensions of Scale in Ecology, Resource Management and Society*, *in* ECOLOGICAL SCALE: THEORY AND APPLICATIONS 499, 503-07 (David L. Peterson & V. Thomas Parker eds., 1998).

120. Parker & Pickett, *supra* note 115, at 20.

121. LEVIN, *supra* note 91, at 71 ("[W]hat we call a community or ecosystem is often a fiction, an arbitrary restriction of spatial boundaries rather than a reflection of real thresholds of species change.").

122. BROWN, *supra* note 52, at 202 (1995) (concluding that there is a trend toward increasing complexity of all of the individuals, societies, and species that make up the global biota.). *See also* C.S. Holling et al., *Science, Sustainability and Resource Management*, *in* LINKING SOCIAL AND ECOLOGICAL SYSTEMS: MANAGEMENT PRACTICES AND SOCIAL MECHANISMS FOR BUILDING RESILIENCE 342, 350-52 (Fikret Berkes et al. eds., 1998).

linked to other ecological processes.[123] In any complex system, the fine details of the system may be linked to large outcomes; the favorite metaphor is the flapping of a butterfly's wings that leads to a hurricane.[124]

Modern complexity theory suggests that the non-linear nature of interrelationships within complex systems requires new analytical processes.[125] Many large-scale ecologists believe that the chaotic nature of ecological processes[126] requires analysis of natural systems from extensive geographic and temporal perspectives.[127] From large space and time scales, the regularity of chaotic systems often emerges in patterns that cannot be seen at smaller scales.[128]

3. Ecological Systems Are Hierarchical

Ecologists increasingly endorse what they call the "hierarchy theory" of ecology.[129] When ecologists refer to the relationships among ecological systems as "hierarchical,"[130] they mean that ecological systems appear to be "hierarchically" structured as a natural consequence of the operation of evolution on the underlying thermodynamic processes by which ecological systems receive and

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123. UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, OFFICE OF FEDERAL ACTIVITIES, CONSIDERING ECOLOGICAL PROCESSES IN ENVIRONMENTAL IMPACT ASSESSMENTS 31-36 (1999).

124. VALERIE AHL & T.F.H. ALLEN, HIERARCHY THEORY: A VISION, VOCABULARY, AND EPISTEMOLOGY 11 (1996).

125. LEVIN, *supra* note 91, at 69 ("Nonlinearity means that one must examine evolution as a set of problems in game theory: a winning type is not necessarily the best of all solutions, judged against some absolute standard; rather, it is a type that, once established in the population, cannot be displaced.... It assumes that the broad outlines of evolutionary adaptation in the face of environmental change may be predictable. But the details are not."). For a critique of complexity theory by a prominent biologist, see EDWARD O. WILSON, CONSILIENCE: THE UNITY OF KNOWLEDGE 85-95 (1998). For a leading historian's perspective, see Donald Worster, *The Ecology of Order and Chaos*, *in* OUT OF THE WOODS: ESSAYS IN ENVIRONMENTAL HISTORY 3, 13-17 (Char Miller & Hal Rothman eds., 1997).

126. In a chaotic model, small differences in initial conditions can lead to radically different outcomes quite quickly. AHL & ALLEN, *supra* note 124, at 5-7. For a discussion of chaos and complexity theories in relation to ecological systems, see J.B. Ruhl, *Thinking of Environmental Law as a Complex Adaptive System: How to Clean Up the Environment by Making A Mess of Environmental Law*, 34 HOUS. L. REV. 933, 945-47 (1997); Gerald Andrews Emison, *The Potential for Unconventional Progress: Complex Adaptive Systems and Environmental Quality Policy*, 7 DUKE ENVTL L. & POL'Y F. 167 (1996).

127. Howard V. Cornell & Ronald H. Karlson, *Local and Regional Processes as Controls of Species Richness*, *in* SPATIAL ECOLOGY: THE ROLE OF SPACE IN POPULATION DYNAMICS AND INTERSPECIFIC INTERACTIONS 250, 252-53 (David Tilman & Peter Kareiva eds., 1997).

128. MAURER, *supra* note 102, at 35. Ecological patterns observed at a single scale often do not extrapolate to other scales. Kevin J. Gaston & Tim M. Blackburn, *A Critique for Macroecology*, 84 OIKOS 353, 355 (1999).

129. Jianguo Wu & Orie L. Loucks, *From Balance of Nature to Hierarchical Patch Dynamics: A Paradigm Shift in Ecology*, 70 Q. REV. BIOLOGY 439 (1995); AHL & ALLEN, *supra* note 124.

130. King, *supra* note 100, at 190-98.

transform solar energy.[131] The term "hierarchy" is perhaps an unfortunate one in view of its connotations of dominance and subservience,[132] but ecologists are not using it in that sense; instead, it refers to the separate, but interrelated, layers and phases by which ecological systems can be classified.[133]

Hierarchy theory posits that ecological systems should not be viewed from a single window or observation set.[134] The complexity of ecological systems can be understood only by analysis from a variety of scales, both geographic and temporal.[135] As the National Research Council recently opined, "Over the past decade, ecologists have gained an awareness of the critical importance of scale."[136] This means that no ecosystem can be arbitrarily defined in space or time.[137] Instead, it must be defined relative to the scale of the issue being analyzed.[138] Within a forest, for example,[139] a particular

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131. R.V. O'NEILL ET AL., A HIERARCHICAL CONCEPT OF ECOSYSTEMS 101-04 (1986).

132. C.S. Holling & Steven Sanderson, *Dynamics of (Dis)harmony in Ecological and Social Systems*, *in* RIGHTS TO NATURE: ECOLOGICAL, ECONOMIC, CULTURAL, AND POLITICAL PRINCIPLES OF INSTITUTIONS FOR THE ENVIRONMENT 57, 77-79 (Susan Hanna et al. eds., 1996).

133. *See* EUGENE P. ODUM, ECOLOGY AND OUR ENDANGERED LIFE-SUPPORT SYSTEMS 25 (1993). "Hierarchy theory . . . does not involve causal mechanisms that work from the top down, but rather posits complex communication both upward and downward across all levels." *See* Bryan Norton, *Change, Constancy, and Creativity: The New Ecology and Some Old Problems*, 7 DUKE ENVTL L. & POL'Y. F. 49, 64 (1996). *See also* C.S. Holling, *Understanding the Complexity of Economic, Ecological, and Social Systems*, 4 ECOSYSTEMS 390, 392-93 (2001) (each level of an ecological system is protected from above by slower, larger levels, but also invigorated from below by faster, smaller cycles of innovation).

134. "Ecosystem processes operate over a wide range of spatial and temporal scales, and . . . [t]here is no single appropriate scale or time frame for management." Norman L. Christensen et al., *The Report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management*, 6 ECOLOGICAL APPLICATIONS 665, 669 (1996). The scales detected by a bird, elk, gopher, or beetle would be very different. Wu & Loucks, *supra* note 129, at 446. "It is probably no accident that hierarchy theory has emerged in the same intellectual climate that spawned deconstructionist perspectives, for both open the door to unexpected levels of analysis." AHL & ALLEN, *supra* note 124.

135. *See* John A. Bissonette, *Scale-Sensitive Ecological Properties: Historical Context, Current Meaning*, *in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 3, 13-17 (John A. Bissonette ed., 1997).

136. NAT'L RESEARCH COUNCIL, *supra* note 3, at 54.

137. *See* Robert Costanza et al., *Modeling Complex Ecological Economic Systems*, 43 BIOSCIENCE 545, 548-49 (1993); Dale et al., *supra* note 47, at 649.

138. O'NEILL ET AL., *supra* note 131, at 85-86. The hierarchy theory of ecology has been described as a way of making it possible to work with "middle number systems" that have traditionally been impossible to predict.

> You can predict a planetary orbit because this is a small-number system of sun and planet. You can predict the weight of a volume of air because this is a large-number system of very many particles. But you cannot predict the weather next week, much less next year, because this is a complex, middle-number system . . . . There are many interacting parts, too many to analyze one at a time, too few to just average. With hierarchy theory, by selecting a specific observation set and locating

stand of trees may be an appropriate level on which to measure the response of soil microbes to short-term weather, but a whole watershed might be needed to recognize patterns of reproduction of trees in relation to twenty-year precipitation cycles, while a study of regrowth after hurricanes might require the study of an entire region.[140] Harvard ecology professor Richard Forman has suggested that with our growing ability to investigate larger time and space scale, "[i]t is unethical to consider an area in isolation from its surroundings or from its development over time."[141]

Hierarchy theory focuses on ecological system dynamics.[142] It recognizes that in our observations of nature: (1) "every measuring or modeling effort takes place from some specified viewpoint, and a scale must be specified from that viewpoint"; (2) spatial and temporal scales are correlated, in that "smaller subsystems change more rapidly than do the larger systems in which they are embedded"; and (3) "the dynamics of nature are sufficiently distinct that different levels can be described in relatively discrete terms."[143]

> within that set distinct scales that allow you to divide the many parts into levels, . . . [y]ou can develop a small-number explanation within the level.

Robert V. O'Neill & Anthony W. King, *Homage to St. Michael; or, Why Are There So Many Books on Scale?*, *in* ECOLOGICAL SCALE: THEORY AND APPLICATIONS 3, 13-14 (David L. Peterson & V. Thomas Parker eds., 1998).

139. For a specific example, see table 4 in C.S. Holling, *Cross-Scale Morphology, Geometry, and Dynamics of Ecosystems*, 62 ECOLOGICAL MONOGRAPHS 447, 479 (1992).

140. *See* O'NEILL ET AL., *supra* note 131, at 85-91. Similarly, the ecological processes that shape the North American prairie appear to be very different depending on the scale from which the processes are viewed.

> At relatively large scales, climatic features such as precipitation and precipitation-soil interaction sort the pool of prairie species into different groupings. In the eastern reaches of the prairie, the presence or absence of fire sorts between prairie and forest dominance, but at finer scales throughout the biome, the frequency of fire sorts prairie species into different assemblages. Local-scale differentiation among prairie species can be effected by large grazers, small disturbances such as . . .(badger) mounds, differentiation in use by pollinators, and competition. All the processes that sort prairie species are characterized by different scales of frequency, duration and magnitude.

V. Thomas Parker & Steward T.A. Pickett, *Historical Contingency and Multiple Scales of Dynamics Within Plant Communities*, *in* ECOLOGICAL SCALE: THEORY AND APPLICATIONS 171, 189-90 (David L. Peterson & V. Thomas Parker eds., 1998) (citations omitted).

141. Richard T.T. Forman, *The Ethics of Isolation, the Spread of Disturbance, and Landscape Ecology*, *in* LANDSCAPE HETEROGENEITY AND DISTURBANCE 213, 227 (Monica Goigel Turner ed., 1987)

142. *See* C.S. Holling, *New Science and New Investments for a Sustainable Biosphere*, *in* INVESTING IN NATURAL CAPITAL: THE ECOLOGICAL ECONOMICS APPROACH TO SUSTAINABILITY 57, 65 (AnnMari Jansson et al. eds., 1994).

143. Bryan G. Norton, *A Scalar Approach to Ecological Constraints*, *in* ENGINEERING WITHIN ECOLOGICAL CONSTRAINTS 45, 52 (Peter C. Schulze ed., 1996). *See also* Holling, *supra* note 139, at 452.

Larger ecological systems "1) behave at relatively low frequencies, 2) behave with less integrity, 3) offer context, and therefore 4) constrain lower entities."[144]

In many instances, ecologists refer to ecological systems as "nested" within other systems of larger scale.[145] Typically, ecologists study not only the "focal level," the level at which the process or phenomenon being studied operates, but at least the levels above and below. "The higher level provides a context and imposes top-down constraints" on the levels below, while the lower level provides mechanisms by which ecological processes operate, and those mechanisms may impose "bottom-up" constraints.[146] While study of the life history of an individual plant or animal (known as "autecology"[147]) may give us valuable information, only multi-level studies can help us learn the principles[148] that determine whether populations of such organisms can maintain themselves.[149]

B. Natural Areas Contain Internal Mechanisms for Change

One of the most interesting aspects of the large scale ecologist's perspective on nature is the appreciation of how ecological systems change over time by adapting to new environmental conditions in an evolutionary fashion without any overall objective except the pursuit of continuing fitness by the various animals and plants that comprise the system.[150]

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144. AHL & ALLEN, *supra* note 124, at 107. *See also* Holling, *supra* note 133.

145. King, *supra* note 100, at 190; Wu & Loucks, *supra* note 129, at 459. *See generally* Wade B. Worthen, *Community Composition and Nested-Subset Analyses: Basic Descriptors for Community Ecology*, 76 OIKOS 417 (1996).

146. Wu & Loucks, *supra* note 129, at 451. For a discussion of the problems caused by failure to evaluate nestedness, see Worthen, *supra* note 145.

147. A DICTIONARY OF ECOLOGY 36 (Michael Allaby ed., 2d ed. 1998) (defining autecology as the "ecology of individual organisms and populations").

148. Landscape ecologists Jim Sanderson and Larry Harris cite examples of the kind of fundamental processes that govern these interrelationships: (1) "Generalist species are more likely to be found along edges or ecotones that are avoided by specialist species"; (2) "Processes within landscape fragments are affected by processes acting in proximate fragments. The impact of the effect extends beyond the boundary of the fragment and depends upon the strength of the process"; (3) "Corridors increase population persistence in fragmented landscapes"; and (4) "Processes within landscape fragments are affected by external processes whose origin, time of arrival, and strength of impact cannot be known in advance. Nevertheless, with certainty an external process will severely negatively impact natural functioning processes within the landscape fragment." Jim Sanderson & Larry D. Harris, *Brief History of Landscape Ecology*, *in* LANDSCAPE ECOLOGY: A TOP-DOWN APPROACH 94-95 (Jim Sanderson & Larry D. Harris eds., 2000).

149. May, *supra* note 104, at 14.

150. *See* Simon A. Levin, *Ecosystems and the Biosphere as Complex Adaptive Systems*, 1 ECOSYSTEMS 431 (1998). *See generally* SCOTT CAMAZINE ET. AL., SELF-ORGANIZATION IN BIOLOGICAL SYSTEMS (2001).

1. Natural Areas are Adaptive

Evolution is continually reshaping ecological patterns and processes. Princeton ecologist Simon Levin says that the elements of a natural area adapt to the changes in their environment in an evolutionary fashion:

> Natural selection, together with other drivers of evolutionary change such as mutation, recombination, environmental factors, and simply chance events, provides the central organizing principle for understanding how the biosphere came to be, and how it continues to change. No teleological principles are at work at the level of the whole system, or even at the local level.[151]

As each organism adapts to its environment, it also modifies its environment, sometimes in minute ways and sometimes more dramatically.[152] Meanwhile, the environment is continually changing as a result of landscape processes, such as soil erosion, storm damage, or subsidence. "The result is a coupled, complex, dynamic system of organism and environment, wherein natural selection optimizes the fitness of populations amid a continually changing, biotically driven environment."[153]

The recognition of the complex scale of ecological processes has revived interest in the idea that evolution operates on the scale of the community as well as the individual.[154] An increasing number

151. LEVIN, *supra* note 91, at 23 ("The biosphere is a complex adaptive system in which the never-ending generation of local variation creates an environment of continual exploration, selection, and replacement."). *But see* ALEXANDER F. SKUTCH, HARMONY AND CONFLICT IN THE LIVING WORLD 141 (2000) (hard to imagine a universe devoid of teleology).

152. *See* Wiens, *supra* note 110, at S99-100.

153. Thompson et al., *supra* note 18, at 20.

154. "Mutualism" is the term applied to relationships between different organisms that are beneficial to each. A classic example is the relationship between a seed-bearing tree and the birds that it relies on to distribute its seeds. CHARLES J. KREBS, ECOLOGY: THE EXPERIMENTAL ANALYSIS OF DISTRIBUTION AND ABUNDANCE 316-17 (4th ed. 1994). When two or more species live together in close association and have mutualistic relationships the relationship is called "symbiosis." A DICTIONARY OF ECOLOGY, *supra* note 147, at 396. In evolutionary biology, the increasing interest in microscopic forms of life has led to a growing interest in group selection phenomena. Many single organisms are now recognized to consist of highly integrated multispecies communities whose members may have previously led a more independent existence. As biologists have gained increased abilities to understand small organisms, they have learned that animals, including humans, have a symbiotic relationship with bacteria that live in the animal's body. "We could not digest and absorb food properly without our gut 'flora'." STEPHEN JAY GOULD, FULL HOUSE: THE SPREAD OF EXCELLENCE FROM PLATO TO DARWIN 184 (1996).

of biologists now believe that communities of organisms can evolve as a group.[155] Evolutionary pluralism, as the famous Harvard biologist Ernst Mayr calls it, accepts the fact that evolution can occur in many different ways among different species.[156] The study of the application of evolutionary group selection to complex system dynamics can lead to greater understanding of the way ecological communities function.[157]

2. Ecological Systems Can Be Self-Organizing

If an ecological system's complex mixture of adaptations is successful in preventing a "collapse" of the system it is said to be a self-organizing system[158] capable of fighting off external forces such as pollution or predation.[159] The strength of an ecological system's self-organizing capacity determines its "resilience;" i.e., its capacity to respond to the stresses and shocks imposed by predation or pollution from external sources.[160]

As complex, self-organizing systems, ecological systems can switch between different modes of behavior as environmental

155. David Sloan Wilson, *Biological Communities as Functionally Organized Units*, 78 ECOLOGY 2018, 2020 (1997). Group selection was out of fashion in evolutionary biology during the period when it was believed that the gene served as the sole unit of selection. ERNST MAYR, TOWARD A NEW PHILOSOPHY OF BIOLOGY: OBSERVATIONS OF AN EVOLUTIONIST 118-19 (1988). However, subsequent research has cast doubt on the reductionist premise that genic selection is the only way in which evolution operates. *See* David Sloan Wilson, *The Group Selection Controversy: History and Current Status*, 14 ANN. L. REV. OF ECOLOGY & SYSTEMATICS 159 (1983). Although selection at the genic level is still recognized as being of major importance, there has been a resurgence of interest in group selection. *See* V.C. WYNNE-EDWARDS, EVOLUTION THROUGH GROUP SELECTION 320-26 (1986) (discussing mutualistic relationships that are hard to account for except by group selection); SKUTCH, *supra* note 151, at 147 (group selection may promote the genetic diversity that insures against failure to adapt to a changing environment).

156. ERNST MAYR, ONE LONG ARGUMENT: CHARLES DARWIN AND THE GENESIS OF MODERN EVOLUTIONARY THOUGHT 149, 157 (1991) ("Some species are, while others are not, subject to group selection.").

157. Wilson, *supra* note 155, at 2023.

> When natural selection operates at the community level, all of the species in a local community become part of a single interacting system that produces a common phenotype, more like genes than species as we usually think of them, and the local community acquires the properties of adaptation that we usually associate with individuals.

Id. at 2024. Some game theorists now believe that cooperation among members of a group may be an evolutionary successful adaptation even in the absence of reciprocity. *See* Rick L. Riolo et al., *Evolution of Cooperation Without Reciprocity*, 414 NATURE 441 (2001).

158. Norton, *supra* note 133, at 64. *See also* Ruhl, *supra* note 126, at 947.

159. EDWARD B. BARBIER ET AL., PARADISE LOST? THE ECOLOGICAL ECONOMICS OF BIODIVERSITY 25-27 (1994) ("Hierarchy theory views ecological systems as complex, multilayered systems that are self-organizing . . . .").

160. *Id.* at 25-27. *See also* Steve Carpenter et al., *From Metaphor to Measurement: Resilience of What to What?*, 4 ECOSYSTEMS 765 (2001).

conditions change. Self-organization allows systems to change as a result of the characteristics of the constituent species, not solely by waiting for the results of evolutionary selection. For example, a tropical savanna is continually being exposed to droughts, floods, differences in soil nutrients, and an intermittent fire regime. These fluctuations change the local species composition and abundance, but to an ecologist the system is merely "exploring" all of the states that the system can assume and still be considered a tropical savanna.[161]

Hierarchy theory views ecological systems as complex, multilayered systems that communicate both upward and downward across all levels of nature with a "creative force, which we now know depends upon a mix of stable, predictable elements and chaotic, unpredictable ones."[162] All ecological systems are subject to destabilizing influences, such as invasive species, climate variation and erosion, that help maintain diversity and resilience in ecological systems, but self-organizing characteristics are important in maintaining productivity and in facilitating recovery from disturbance.[163]

The use by ecologists of the term "self-organizing" does not imply that ecological systems are superorganisms that operate in some teleological fashion, as once was believed.[164] It means that if a natural area is left alone, the normal processes of evolutionary adaptation will cause the system to organize itself, although it will do so in a way that is predictable only in general terms.[165] Research into self-organization is focusing on processes such as energy cascading, material cycling and information organizing. Chaos and complexity theories offer intriguing possibilities but remain to be fully fleshed out.[166]

C. Ecological Processes Are as Important as Ecological Patterns

Ecology originated as an attempt to classify and study the relation of various organisms to landscape patterns, focusing on apparently discrete entities such as bogs, dunes, or prairies.[167]

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161. Solbrig, *supra* note 80, at 109-10.

162. Norton, *supra* note 133, at 64.

163. C. S. Holling, *Engineering Resilience versus Ecological Resilience*, *in* ENGINEERING WITHIN ECOLOGICAL CONSTRAINTS 31, 32 (Peter C. Schulze ed., 1996).

164. *See generally* Norton, *supra* note 133.

165. For an interesting account of the attempt to use complexity theory to bring order to ecological systems (among other complex adaptive systems), see PER BAK, HOW NATURE WORKS: THE SCIENCE OF SELF-ORGANIZED CRITICALITY 121-27 (1996).

166. Henry A. Regier, *The Notion of Natural and Cultural Integrity*, *in* ECOLOGICAL INTEGRITY AND THE MANAGEMENT OF ECOSYSTEMS 3, 5 (Stephen Woodley et al. eds., 1993)

167. DONALD WORSTER, NATURE'S ECONOMY: A HISTORY OF ECOLOGICAL IDEAS 192-94 (2d

Early biogeographers, who created maps showing the distribution of communities of animals and plants, played an important role in increasing the awareness of differences among ecological patterns.[168] Some ecologists have now opined that although landscape patterns "look pretty interesting," they have little intrinsic significance except in the context of ecological processes.[169] This view is perhaps extreme, and the study of patterns remains an important part of ecology,[170] but most contemporary ecologists do at least tend to emphasize process as well as pattern.[171]

What is an ecological process? Like ecosystems, processes can be defined by aggregation and subdivision in various ways. A basic division usually starts by separating landscape level processes from processes internal to the ecological system:

1. Landscape Level Processes

Landscape ecologist Larry Harris and his colleagues identify four categories of landscape-level ecological processes: (1) external forces unrelated to biological processes, such as hurricanes, glaciers, or floods; (2) physical forces dependent on biota for propagation, such as wildfire; (3) biological landscape processes, such as the changes in the landscape created by beavers building dams or elephants trampling vegetation; and (4) human impacts on the landscape, such as habitat modification and pollution.[172]

Large scale ecology, in combination with expertise from other scientific disciplines, has greatly improved our understanding of

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ed. 1994).

168. *See, e.g.*, ROSCOE POUND & FREDERIC E. CLEMENTS, THE PHYTOGEOGRAPHY OF NEBRASKA (1900). The field of biogeography continues to specialize in the spatial aspects of the distribution of organisms. *See generally* ANALYTICAL BIOGEOGRAPHY: AN INTEGRATED APPROACH TO THE STUDY OF ANIMAL AND PLANT DISTRIBUTIONS (A.A. Myers & P.S. Giller eds., 1988).

169. Roy Haines-Young, *Landscape Pattern: Context and Process*, *in* ISSUES IN LANDSCAPE ECOLOGY 33 (John A. Wiens & Michael R. Moss eds., 1999).

170. Dale et al., *supra* note 47, at 651-53.

171. Sanderson & Harris, *supra* note 148, at 16. The goal should be "the restoration of natural ecological processes across the landscape rather than the maintenance of certain landscape patterns." For a discussion of ethical issues in ecological restoration, see Alyson C. Flournoy, *Restoration Rx: An Evaluation and Prescription*, 42 ARIZ. L. REV. 187 (2000); C. Mark Cowell, *Ecological Restoration and Environmental Ethics*, 15 ENVTL. ETHICS 19 (1993).

172. Larry D. Harris et al., *Landscape Processes and Their Significance to Biodiversity Conservation*, *in* POPULATION DYNAMICS IN ECOLOGICAL SPACE AND TIME 319, 328-37 (Olin E. Rhodes, Jr. et al. eds., 1996). *See also* Norman L. Christensen, Jr., *Managing for Heterogeneity and Complexity on Dynamic Landscapes*, *in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 167, 178 (S.T.A. Pickett et al. eds., 1997) (ecological patterns are often greatly affected by "chance" events like weather variation).

these processes.[173] Hurricanes, for example, can be observed on a worldwide scale, and the history of the ecological effects of these storms can be tracked in broad terms on the scale of centuries,[174] and in more detail on the scale of years.[175] Our understanding of the history and geography of wildfire ecology has improved greatly and has begun to influence national policy.[176]

And of prime importance, we have become better able to analyze the impacts of our own influence on nature; when we step back and look at the big picture both geographically and historically, we can observe patterns of impact that would not be apparent otherwise.[177] For example, large scale comparison of the sites of the remaining populations of the endangered California red-legged frog with sites formerly occupied by the frog showed a strong positive association of the abandoned sites with nearby agricultural activity, suggesting that pesticide application may be contributing to the frog's extinction.[178] And numerous studies of changing habitats over large time and space scales have revealed the impact of climate change on a wide range of plants and animals.[179]

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173. For example, a biochemical analysis of Hawaiian forest soils demonstrated that many of the nutrients in the soils came from dust that had been transported by wind from Central Asia, over 6000 kilometers away, during dry periods in geologic history. O.A. Chadwick et al., *Changing Sources of Nutrients During Four Million Years of Ecosystem Development*, 397 NATURE 491 (1999).

174. Emery R. Boose et al., *Landscape and Regional Impacts of Hurricanes in New England*, 71 ECOLOGICAL MONOGRAPHS 27 (2001).

175. Hans W. Paerl et al., *Ecosystem Impacts of Three Sequential Hurricanes (Dennis, Floyd, and Irene) on the United States' Largest Lagoonal Estuary, Pimlico Sound, NC*, 98 PROC. NAT'L ACAD. SCI. USA 5655 (2001).

176. *See infra* text accompanying notes 667-699.

177. "The appropriate domains of causality in many ecological studies could extend far beyond previously assumed spatial and temporal bounds." Thompson et al., *supra* note 18, at 21. Thompson and his co-authors also suggest the need for research to determine whether landscape-level processes create biophysical constraints on a site that produce what complexity theorists would call an "evolutionary attractor" that establishes a model of organism function that evolution would try to achieve. *Id. See also* ROBERT WESSON, BEYOND NATURAL SELECTION 144-50 (1991) (the genome is a series of linked attractors at all levels of genetic stability).

178. Carlos Davidson et al., *Declines of the California Red-legged Frog: Climate, UV-B, Habitat, and Pesticides Hypotheses*, 11 ECOLOGICAL APPLICATIONS 464, 474-75 (2001). The study also found that many of the formerly occupied sites were at higher elevations than those still occupied; there has been a worldwide decline in amphibian populations, particularly at high elevations, for reasons that biologists do not yet understand. *Id.* at 473-474. The authors of the study do not claim that they have identified the exact cause of the decline in the frog population, but the study appears to make it unlikely that the decline is solely the result of competition with non-native bullfrogs. *Id.* at 475-76.

179. *See infra* text accompanying notes 468-79.

2. Internal Ecological Processes

Internal ecological processes include those processes resulting from the interaction of the organisms in an area. Thomas Parker and Steward Pickett divide these into five categories:

> (1) the movements and interactions of individual organisms;
> (2) the transformation of energy and materials;
> (3) the successional replacement of one set of species by another;
> (4) the changes in size and composition of particular patches of habitat, and
> (5) the responses of the area to regional or global scale environmental change.[180]

The first three of these processes have been traditional subjects of ecological study. Haeckel, the founder of the term ecology, defined it as the study of the interaction of organisms and their environment.[181] Lindeman's pioneering study,[182] followed by Odum's extensive work, looked at the flow of energy through natural systems.[183] Early ecologists like Clements and Cowles focused on the succession of plants and animals in changing landscapes.[184]

The fourth and fifth of these categories have been of particular interest in recent years. The ability to view landscapes from larger spatial and temporal scales has shown us a kaleidoscopic pattern of landscape patches that come and go over time. The study of these movements is known as the study of "patch dynamics," and it has significantly affected ecologists' ideas about the natural world.[185] And the impact of climate change on ecological patterns has recently become one of the most challenging issues of our time.[186]

The internal ecological processes of an area must operate within the ranges set by the landscape level processes. Thus, for example, the biological productivity of an area is limited by soil conditions,

180. Parker & Pickett, *supra* note 115, at 17, 22.
181. ANNA BRAMWELL, ECOLOGY IN THE 20TH CENTURY: A HISTORY 40 (1989).
182. WORSTER, *supra* note 167, at 306-09.
183. ODUM, *supra* note 133, at 32-35.
184. PETER J. BOWLER, THE NORTON HISTORY OF THE ENVIRONMENTAL SCIENCES, 373-76 (1993).
185. *See infra* text accompanying notes 225-35.
186. *See infra* text accompanying notes 457-91.

water availability, and climate,[187] and while "chronic human intervention may broaden these ranges," it "cannot entirely evade the constraints of place."[188]

Many ecological processes confer enormous benefits on the human race, such as purification of air and water, pest control, flood abatement, pollination, climate regulation, and soil nutrient cycling; this has led to a movement toward trying to quantify the benefits of "ecosystem services" in an effort to increase public comprehension of the importance of these processes.[189] Contemporary ecology increasingly recognizes that landscape-level processes, including both the natural changes in the landscape resulting from fire and storms and the changes resulting from human activities, must be studied along with changes internal to the ecological systems themselves if ecological processes are to be correctly understood.[190] Analysis of the interaction of the landscape level and internal processes requires consideration of a wide range of scales,[191] from centimeters to hundreds of kilometers.[192]

A focus on the protection of ecological processes is seen by some ecologists as a way to avoid getting bogged down in the details of hundreds or thousands of individual species, thereby losing sight of the forest for the trees.[193] Conservation biologists, who work out in

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187. John J. Ewel, *Ecosystem Processes and the New Conservation Theory*, *in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 252, 259 (Steward Pickett et al. eds, 1997) ("To sustain biological richness, the abiotic features of the ecosystem must be retained, and in the case of terrestrial ecosystems the most vulnerable abiotic factor is soil fertility.").

188. Dale et al., *supra* note 47, at 651-52 ("For instance, enhanced productivity on desert uplands can be supported over the short term by additions of water; however, higher productivity generally cannot be sustained in arid-land soils over the long run because of the degrading effects of high evapotranspiration rates and resulting salinization."). *See also* Ken Lertzman & Joseph Fall, *From Forest Stands to Landscapes: Spatial Scales and the Roles of Disturbances*, *in* ECOLOGICAL SCALE: THEORY AND APPLICATIONS 339, 349 (David L. Peterson & V. Thomas Parker eds., 1998) ("The effects of local conditions of soil and microclimate on vegetation are ubiquitous.").

189. *See, e.g.*, Robert L. Fischman, *The EPA's NEPA Duties and Ecosystem Services*, 20 STAN. ENVTL. L.J. 497 (2001).

190. Monica G. Turner, *Ecological Dynamics at Broad Scales: Ecosystems and Landscapes*, *in* SCIENCE AND BIODIVERSITY POLICY S-29, S-34 (BioScience Supplement, 1995).

191. Paul G. Risser, *Landscape Ecology: The State of the Art*, *in* LANDSCAPE HETEROGENEITY AND DISTURBANCE 3, 12 (Monica Goigel Turner ed., 1987).

192. Plant growth, for example, is determined by vegetative processes that operate at scales of centimetres to tens of metres and days to decades. At the other extreme, slow geomorphological processes define basic topography and soil composition at very large scales. "In between, contagious disturbance processes such as fire, insect outbreak, plant disease, and water flow form patterns over spatial scales of tens of metres to hundreds of kilometres." Holling, *supra* note 139, at 484.

193. Daniel Simberloff, *Flagships, Umbrellas, and Keystones: Is Single-Species Management Passé in the Landscape Era?*, 83 BIOLOGICAL CONSERVATION 247, 252 (1998) ("The emphasis on processes automatically leads to a broad spatial scale with a focus on landscapes . . . . Thus, ecosystem management, though not simply the management version of landscape

the real world to try to apply principles of ecology to particular problems, sometimes worry that too much focus on process might be used as an excuse to downplay the importance of individual rare species and the protection they get from the Endangered Species Act,[194] but no one denies that improved understanding of ecological processes is desirable.

III. LEARNING FROM LARGE-SCALE PROCESSES

The large-scale ecologists' study of ecological processes at a wide range of scales has led to significant advances in ecological theory. By expanding the size of the area and the length of time covered by ecological studies, ecologists have cast new light on some propositions that had been widely accepted and have developed new theories that better explain ecological phenomena. Some of the most visible and apparently drastic changes in the environment appear cyclical when viewed from a larger scale. But on the other hand, many of the cumulative effects of small scale changes that all go in the same direction have grave implications that ecologists cannot forecast because they are outside the parameters of historical experience.

A. *Competition Doesn't Always Cause Extinction*

"Competitive exclusion," the idea that all continued competition between different species would eventually end with the extinction of the weaker competitor, was a mainstay of biological theory for over a century.[195] Ever since Darwin's time, scientists have studied the role of competition among species, and many have tended to assume that over time the better competitor would eliminate the weaker competitor.[196]

ecology, is very closely related to the latter discipline.").

194. REED F. NOSS & ALLEN Y. COOPERRIDER, SAVING NATURE'S LEGACY: PROTECTING AND RESTORING BIODIVERSITY 90-91 (1994). For expressions of concern that "process" may be given too much emphasis today, see Simberloff, *supra* note 193, at 251-54; Oliver A. Houck, *On the Law of Biodiversity and Ecosystem Management*, 81 MINN. L. REV. 869, 974-75 (1997).

195. The idea that competitive exclusion was a universal phenomena that could be predicted mathematically dates back to the 1930s. A DICTIONARY OF ECOLOGY, *supra* note 147, at 93-94. For an overall analysis of past and current ideas about competitive exclusion, see TOKESHI, *supra* note 53, at 215-48.

196. *See, e.g.*, GEORGE GAYLORD SIMPSON, THE MEANING OF EVOLUTION 221-24 (1949). The term "survival of the fittest" was coined by Herbert Spencer, later adopted by Darwin, and frequently used in ways unintended by either Spencer or Darwin. PETER J. BOWLER, EVOLUTION: THE HISTORY OF AN IDEA 240-42, 342-43 (rev. ed. 1989). *See also* ERNST MAYR, EVOLUTION AND THE DIVERSITY OF LIFE 74-75 (1976) (Darwin used fitness in the sense of being well adapted to the environment).

1. Nature's Puzzling Variety

Despite the wide acceptance of the competitive exclusion theory, the theory rarely seemed to play out in practice.[197] Ecologists have long been puzzled why so many species continue to exist in the face of competition.[198] The apparent inconsistency between theory and observation has encouraged extensive empirical analysis of other processes that might be forestalling competitive exclusion.[199] Modern studies of natural areas have continued to find many more coexisting species (i.e., greater "species richness") than the theory of competitive exclusion would have predicted.[200] "Even highly competitive assemblages such as freshwater fish and songbirds are unsaturated, suggesting that interspecific competition is not sufficient to produce a ceiling on local richness."[201]

Today, with the longer time and larger space horizons of large scale ecology, it is apparent that the theory of competitive exclusion can operate only under hypothetical conditions of environmental stability that are seldom found in nature. The primary failing of the theory was its inherent assumption that ecological systems were often in an equilibrium state.

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197. HUBBELL, *supra* note 39, at 10-11 ("[t]he number of cases in which local extinction can be definitively attributed to competitive exclusion is vanishingly small.").

198. The classic paper calling attention to the issue was G.E. Hutchinson, *Homage to Santa Rosalia, or Why Are There So Many Kinds of Animals?* 93 AMERICAN NATURALIST 145 (1959). *See also* CHARLES ELTON, ANIMAL ECOLOGY 27 (1927) ("[s]uccession . . . does not take place with the beautiful simplicity which we could desire . . . ."); STEPHEN J. GOULD, WONDERFUL LIFE: THE BURGESS SHALE AND THE NATURE OF HISTORY 236-39 (1989) (stating that no evidence shows that extinct creatures fossilized in Burgess Shale were less successful at adaptation than those that survived).

199. James H. Brown, *Two Decades of Homage to Santa Rosalia: Toward a General Theory of Diversity*, 21 AMERICAN ZOOLOGIST 877, 886 (1981) (Stating that ecologists should search for patterns that affect the fitness of species to the environment). Lack of success in competition is often a product of factors other than the process of competition itself. Certain demographic processes, such as the loss of genetic variability, may result in a feedback mechanism that can increase death rates or decrease birth rates. BROWN, *supra* note 52, at 159.

200. *See, e.g.*, Clarence L. Lehman & David Tilman, *Competition in Spatial Habitats*, *in* SPATIAL ECOLOGY: THE ROLE OF SPACE IN POPULATION DYNAMICS AND INTERSPECIFIC INTERACTIONS 185, 191 (David Tilman & Peter Kareiva eds., 1997) (pointing out that in reality, environmental heterogeneity limits the operation of competitive exclusion); Cornell & Karlson, *supra* note 127, at 262-67 (concluding that studies of coral reefs show that various forms of heterogeneity in space and time can forestall competitive exclusion indefinitely).

201. Cornell & Karlson, *supra* note 127, at 250, 267. *See also* S. Joseph Wright, *Plant Diversity in Tropical Forests: A Review of Mechanisms of Species Coexistence*, 130 OECOLOGIA 1, 2 (2002) (discussing various ways in which plants in tropical forests avoid competitive exclusion).

2. Environmental Change May Promote Biological Diversity

A better understanding of the rise and fall of the populations of individual species has come about because of the growing interest of ecologists in expanding the geographic scale of their studies, so that the studies include heterogeneous areas with varied habitats.[202] For example, ecologists now believe that the theory of competitive exclusion failed to take into consideration the extent to which competition is disrupted by environmental variation and change over large areas.[203] Today, ecologists recognize that evolution does not operate in a vacuum.[204] Evolution selects optimal phenotypes only in an environment that varies with regularity. "In an unpredictably variable environment, phenotypes will be selected that can survive the various unpredictable environmental circumstances."[205] As in economic markets, in biological evolution diversity emerges naturally from competition as different species develop varying strategies to adapt to unpredictable environmental change.[206]

In addition, by extending the temporal scale of ecological studies, ecologists can observe population patterns over extended time periods, which enables them to more accurately analyze the effects of environmental change.[207] The availability of longer time series of data has made it apparent that evolution, in response to environmental change, may take place quite rapidly.[208] Jonathan Weiner, in his Pulitzer prize-winning book, *The Beak of the Finch* (1995), called attention to the work of ecologists Peter and Rosemary Grant, whose analysis of the effects of changing environmental conditions on the populations of various species on

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202. *See, e.g.*, Ilkka Hanski, *Effects of Landscape Pattern on Competitive Interactions, in* MOSAIC LANDSCAPES AND ECOLOGICAL PROCESSES 203 (Lennart Hansson et al. eds., 1995).

203. *See, e.g.*, Matt J. Keeling et al., *Reinterpreting Space, Time Lags, and Functional Responses in Ecological Models*, 290 SCI. 1758 (2000).

204. Peter Chesson & Nancy Huntly, *The Roles of Harsh and Fluctuating Conditions in the Dynamics of Ecological Communities*, 150 AM. NATURALIST 519, 521 (1997) ("Environmental fluctuations provide opportunities for temporal niche partitioning but do not fundamentally change the impact of interspecific competition."). The early studies are reviewed in Julie Sloan Denslow, *Disturbance-Mediated Coexistence of Species, in* THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS 307 (S.T.A. Pickett & P.S. White eds.1985).

205. Solbrig, *supra* note 80, at 107. *See* S.T.A. PICKETT & P.S. WHITE, *Patch Dynamics: A Synthesis, in* THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS 371, 373 (S.T.A. Pickett & P.S. White eds., 1985) ("The most obvious role that disturbance plays in ecosystems is in the deflection of a community from some otherwise predictable successional path.").

206. LEVIN, *supra* note 91, at 133.

207. *See, e.g.*, Jason E. Tanner et al., *Species Coexistence, Keystone Species, and Succession: A Sensitivity Analysis*, 75 ECOLOGY 2204 (1994).

208. Thompson, *supra* note 65.

the Galapagos Islands documented rapid evolution in response to environmental change.[209]

Some dominant species may recede to a lesser status if they lack the ability to cope with environmental change, particularly if it is a steady change in the same direction ("unidirectional change"). Such changes have been particularly noticeable in the northern latitudes, where the warming of the climate has been steady and severe.[210] For example, a common bird in the Swedish forests, the collared flycatcher, is experiencing reduced body weight in nestlings.[211] The evolutionary trend toward increased body weight has now apparently been counteracted by a decline in the abundance of the caterpillars on which the birds feed while nesting.[212] The decline appears to be the result of the fact that trees are budding earlier in the warming temperatures, and the caterpillars no longer emerge at the ideal time for the birds' nourishment.[213]

On the other hand, those species that invest heavily in the functions that enable them to weather environmental variability may make trade-offs that weaken their ability to compete in other ways.[214] For instance, "some plant species allocate a high proportion of their mass to their roots," which makes them better able to adjust to fluctuations in soil nutrients. But, by doing so, they "have less [energy] to allocate to other structures, such as leaves, stems, [and] seeds," and thus, may have inferior abilities to

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209. *See also* Peter R. Grant et al., *Effects of El Niño Events on Darwin's Finch Productivity*, 81 ECOLOGY 2442 (2000); Peter R. Grant and B. Rosemary Grant, *Unpredictable Evolution in a 30-Year Study of Darwin's Finches*, 296 SCI. 707 (2002)..

210. ROGER G. BARRY & RICHARD J. CHORLEY, ATMOSPHERE, WEATHER & CLIMATE 351-52 (7th ed. 1998).

211. J. Merila et al., *Cryptic Evolution in a Wild Bird Population*, 412 NATURE 76 (2001).

212. *Id.* at 78. For commentary on this study, see David J. Hosken, *Hidden Change: Cryptic Evolution in Flycatchers*, 16 TRENDS IN ECOLOGY & EVOLUTION 593 (2001).

213. Marcel E. Visser & Leonard J.M. Holleman, *Warmer Springs Disrupt the Synchrony of Oak and Winter Moth Phenology*, 268 PROCEEDINGS OF THE ROYAL SOC'Y OF LONDON 289 (2001). *See also* R. B. Mynemi et al., *Increased Plant Growth in Northern High Latitudes from 1981 to 1991*, 386 NATURE 698 (1997); William E. Bradshaw & Christina M. Holzapfel, *Genetic Shift in Photoperiodic Response Correlated with Global Warming*, 98 PROC. NAT'L ACAD. SCI. U.S. 14508 (2001). Scientists are concerned about the ability of animal species to evolve rapidly enough to adapt to the pace of climate change. "Global warming will occur so quickly that changes in the ecosystem may lag significantly behind (several hundred years behind the climate changes)." FRANCES DRAKE: GLOBAL WARMING: THE SCIENCE OF CLIMATE CHANGE 209 (2000). Comparable climate changes have occurred in the past, but not in so short a time. Harold A. Mooney et al., *Biodiversity and Ecosystem Functioning: Basic Principles*, *in* GLOBAL BIODIVERSITY ASSESSMENT 275, 321 (Vernon H. Heywood ed., 1995).

214. LEVIN, *supra* note 91, at 133 ("Biodiversity feeds on itself in the sense that it is the changing adaptive landscape . . . that makes alternative lifestyles attractive and enhances diversity.").

compete by acquiring light or dispersing seed.[215] Thus, they may appear to be inadequate competitors under any particular set of conditions at a given time or place, but at larger scales, their superior adaptability can be seen.[216]

One result of the more realistic attitude toward competition is a revised attitude toward so-called "exotic species."[217] Concern about the introduction of new species to an area remains high, given the tragic experience that has followed from some past introductions.[218] But, the fatalistic assumption that successful invaders would always drive native species to extinction through competition no longer seems plausible.[219] It is being replaced by case-by-case analysis of particular species relationships.[220]

When some of the earlier postulates of ecology, such as competitive exclusion, failed to hold up under empirical testing, ecologists began to reexamine some of the basic premises of their research.[221] One of the most significant results of that reexamination has been the recognition that too many early ecological theories were based on assumptions of environmental stability that were unscientific in origin.[222] This led ecologists to put new emphasis on the processes of environmental change.

B. *Fragmentation Doesn't Always Reduce Diversity*

Most European settlers in America probably shared what has been called the Tory view of landscape–a romantic attachment to the ideas of continuity and tradition felt to be embodied in the

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215. David Tilman, *Community Diversity and Succession: The Roles of Competition, Dispersal, and Habitat Modification*, *in* BIODIVERSITY AND ECOSYSTEM FUNCTION 327, 329 (Ernst-Detlev Schulze & H.A. Mooney, eds. 1994).

216. *See* Ove Eriksson, *Functional Roles of Remnant Plant Populations in Communities and Ecosystems*, 9 GLOBAL ECOLOGY & BIOGEOGRAPHY 442 (2000).

217. *See, e.g.*, Dov F. Sax & James H. Brown, *The Paradox of Invasion*, 9 GLOBAL ECOLOGY & BIOGEOGRAPHY 363 (2000) (invaders succeed because evolution of native species was limited by the lack of available genetic resources); Michael L. Rosenzweig, *The Four Questions: What Does the Introduction of Exotic Species do to Diversity?*, 3 EVOLUTIONARY ECOLOGY RES. 122 (2001).

218. The classic text is MARK WILLIAMSON, BIOLOGICAL INVASIONS (1996).

219. "We routinely overlook the flexibility, opportunism, and facultative use of resources of which variable individuals in species are universally capable – not to mention potential evolutionary responses. I believe that most species will be found to be far less specialized in resource use than current theory suggests." HUBBELL, *supra* note 39, at 328.

220. *See, e.g.*, NANAKO SHIGESADA & KOHKICHI KAWASAKI, BIOLOGICAL INVASIONS: THEORY AND PRACTICE 109-14 (1997). *See* BROWN, *supra* note 52, at 217-24.

221. HUBBELL, *supra* note 39.

222. The 'balance of nature' was "a concept rooted in Christian and Enlightenment world views." Lakshman Guruswamy, *Integration & Biocomplexity*, 27 ECOLOGY L.Q. 1191, 1204 (2001).

classical European landscapes.[223] Today's ecologists have a much different view of landscape, seeing it more like a kaleidoscope of heterogeneous patches that shift into new configurations frequently.[224] This ecological insight has called into question many popular ideas about the natural world.

1. Patch Dynamics

In large-scale ecology, the natural world is viewed from a distance, both in space and in time. From that perspective, boundaries of ecosystems appear and disappear in a ballet of "patch dynamics,"[225] through which the characteristics of natural areas change as the plants and animals adjust to changing environmental conditions.[226]

The theory of patch dynamics begins by viewing the natural world as a mosaic of individual patches of habitat, rather than as large blocks of space having generally similar characteristics.[227] The dynamics occur as patches of habitat move over time as a result of landscape level processes; the various species in the habitat move in response, and these internal ecological processes further modify the habitat in an unending process that may be very slow or quite rapid.[228] This dynamic ecological theory recognizes that nature is continually changing[229] and that we must evaluate the effects of our activities against this moving target.[230]

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223. NIGEL EVERETT, THE TORY VIEW OF LANDSCAPE 1 (1994). For a cogent analysis of the history of attitudes toward conservation, see JOHN PASSMORE, MAN'S RESPONSIBILITY FOR NATURE 73-100 (1974).

224. The idea that certain landscapes were a "dynamic mosaic of . . . patches" can be traced back to the 1930s. H.H. Shugart, *Equilibrium Versus Non-Equilibrium Landscapes*, *in* ISSUES IN LANDSCAPE ECOLOGY 18, 19 (John A. Wiens & Michael R. Moss eds., 1999). Western hemisphere ecologists typically use the term "patch" to refer to a piece of relatively similar habitat, while some European ecologists prefer the term "ecotope." FARINA, *supra* note 110, at 50-52.

225. *See generally* LIVING IN A PATCHY ENVIRONMENT (Bryan Shorrocks & Ian R. Swingland eds., 1990).

226. Judy L. Meyer, *The Dance of Nature: New Concepts in Ecology*, 69 CHI.-KENT L. REV. 875, 881 (1994).

227. COMM. ON SCIENTIFIC ISSUES IN THE ENDANGERED SPECIES ACT, NAT'L RESEARCH COUNCIL, SCIENCE AND THE ENDANGERED SPECIES ACT 95-97(1995). The EPA sees the pattern and connectivity of habitat patches as an important element of environmental impact analysis. OFFICE OF FEDERAL ACTIVITIES, U.S. EPA, CONSIDERING ECOLOGICAL PROCESSES IN ENVIRONMENTAL IMPACT ASSESSMENTS 17-22 (1999).

228. *See* Wiens, *supra* note 110.

229. Some environmental cycles of change are very familiar, such as the differences in temperature between night and day or between summer and winter. Environmental change is often so short-range that plants and animals "average over them" or shut down and gear back up later, as with diurnal and annual cycles of night and day, warmth and cold, or even longer range cycles of drought and flood. LEVIN, *supra* note 91, at 74.

230. DANIEL B. BOTKIN, DISCORDANT HARMONIES: A NEW ECOLOGY FOR THE TWENTY-FIRST

Patch dynamics is increasingly used as an unifying concept in large scale ecology.[231] For example, a species that appears to be out-competing its rivals at one point in time may appear to be the weaker competitor at a later time when environmental conditions have changed through patch dynamics.[232] Viewed from a hierarchical perspective, in which individual patches of habitat are analyzed from different scales, the process of environmental change can be seen as a valuable attribute of nature rather than an "imbalance" to be corrected.[233]

Because some of the changes in patch dynamics are caused by human intervention, the study of patch dynamics inevitably must look at the ecology of human-created as well as natural patches.[234] Patch dynamics recognizes that humans are part of nature and that the human influence on the environment can often be condemned but rarely ignored.[235]

Where an area is characterized by a wide range of differing patches of habitat, it is referred to as "heterogeneous."[236] In many cases, animals rely heavily on two or more habitats at different seasons, and the proximity of these different habitats creates reciprocal subsidies for the species that inhabit them.[237] For example, a study of the interaction of a forest and a stream in Japan found that aquatic insects emerging in the Spring from the stream provided 25.6% of the annual energy supply of forest birds, while during the summer the terrestrial invertebrates that washed

CENTURY 190 (1990).

231. Wu & Loucks, *supra* note 129, at 449.

232. Judy L. Meyer, *Conserving Ecosystem Function*, *in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 136, 140 (Steward Pickett et al. eds., 1997) (Species may respond differently in the functions they perform as the environment changes).

233. Wu & Loucks, *supra* note 129, at 447 ("Recognition of the scale-dependence and hierarchical structure of patchiness is crucial to understanding the dynamics and stability of ecological systems.").

234. A. Dan Tarlock, *Environmental Law, But Not Environmental Protection*, *in* NATURAL RESOURCES POLICY AND LAW: TRENDS AND DIRECTIONS 178, 188-89 (Lawrence J. MacDonnell & Sarah F. Bates eds., 1993) (conservation biology recognizes interaction of humans and nature).

235. Peter M. Vitousek, *Beyond Global Warming: Ecology and Global Change*, 73 ECOLOGY 1861, 1873 (1994) ("The world has changed as a consequence of human action and will change more; we need to recognize, anticipate, and work with change at the same time as we work to minimize many of its consequences."). FIKRET BERKES, SACRED ECOLOGY: TRADITIONAL ECOLOGICAL KNOWLEDGE AND RESOURCE MANAGEMENT 164 (1999). ("Although much of ecology continues as a conventional reductionistic science, the more holistic approaches in ecology provide a new vision of the earth as an ecosystem of interconnected relationships in which humans are part of the web of life.").

236. RICHARD T.T. FORMAN & MICHAEL GODRON, LANDSCAPE ECOLOGY 473 (1986) (The concept of an ecological "niche" must include "the combination of uses found in a heterogeneous assemblage of ecosystems in a landscape.").

237. Forman, *supra* note 141, at 219-20.

into the stream from the forest constituted 44% of the energy supply of fish in the stream.[238]

Some studies have found a powerful link between habitat heterogeneity and species richness.[239] The fact that habitats are both spatially and temporally heterogeneous[240] has been called "one of the fundamental concepts of modern ecology."[241] Although heterogeneity can be valuable in some cases,[242] in other cases it can work against the cause of conservation.[243] For example, in some island environments extensive heterogeneity has been created by human activities and the introduction of non-native species and diseases; this has driven many native species to or near extinction, as has happened in Hawaii.[244] But in other contexts, heterogeneity may effectively preserve biodiversity by protecting a balance in prey-predator relationships by providing a variety of habitats in which differing predator success rates can be expected.[245]

Ecologists who study microbes point out that we humans are ourselves heterogeneous habitats. As biological technology increasingly allows more effective study of microorganisms, we have become aware of the variety and complex relationships of the microscopic species within our own bodies. Like other animals, we

238. Shigeru Nakano & Masashi Murakami, *Reciprocal Subsidies: Dynamic Interdependence Between Terrestrial and Aquatic Food Webs*, 98 PROC. OF THE NAT'L ACAD. OF SCI., U.S.A. 166 (2001).

239. A recent study of Canadian butterflies shows that the diversity of butterfly species is closely related to the heterogeneity of the environment. Jeremy T. Kerr, *Butterfly Species Richness Patterns in Canada: Energy, Heterogeneity, and the Potential Consequences of Climate Change*, 5 CONSERVATION ECOLOGY (1) 10 (2001), *available at* http://www.consecol.org/vol5/iss1/art10 (last visited Sept. 14, 2001).

240. On the history and meaning of the term, see Robert P. McIntosh, *Concept and Terminology of Homogeneity and Heterogeneity in Ecology*, *in* ECOLOGICAL HETEROGENEITY 24 (Jurek Kolasa & S.T.A. Pickett eds., 1991).

241. NAT'L RESEARCH COUNCIL, *supra* note 227, at 95.

242. S.T.A. Pickett & M.L. Cadenasso, *Landscape Ecology: Spatial Heterogeneity in Ecological Systems*, 269 SCI. 331, 334 (1995).

243. For example, the damage caused by white-tailed deer has increased because of their ability to avoid their predators in small patches of woodland scattered among other habitats. Risser, *supra* note 82, at 8.

244. John J. Ewel, *Ecosystem Processes and the New Conservation Theory*, *in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 252, 258 (Steward Pickett et al. eds, 1997).

245. In homogenous settings, such associations are liable to extinction via ever-diverging cycles of boom and bust of prey populations, interacting with similar but lagged cycles for the predators. But in a heterogeneous, patchy world, the associations can persist as a shifting mosaic of empty patches, prey only patches where prey populations are doing well, and patches with prey and predator where predators are currently flourishing.

May, *supra* note 104, at 7. *See also* Mooney et al., *supra* note 213, at 313 (patch dynamics is an important source of biodiversity).

harbor a heterogeneous mix of living creatures, some of which are essential to our survival while others can be harmful.[246]

Regardless of whether heterogeneity is desirable or not, ecologists tend to view it as an inevitable product of ecological processes – one that needs to be studied rather than avoided.[247] Many biologists have observed a long-range trend toward greater complexity in organisms and greater heterogeneity in their interrelationships.[248] The same processes that create nonequilibrium time dynamics may also create heterogeneous physical structure.[249] It seems likely that the more that ecological systems change over time, the more these changes will result in complex mosaics of habitat in various stages of change.[250]

2. Metapopulation Ecology

Ecologists generally support the idea that we should be protecting natural areas on a large scale,[251] but when priorities must be set, which types of habitat deserve the most protection? Even if our goal is primarily the protection of individual species, the fact that a species may be found in a particular habitat does not necessarily tell us whether and to what extent that habitat is important to that species.[252]

Ecologists refer to the aggregate of individual populations of a species that are occupying many different patches of habitat as a "metapopulation."[253] For example, frogs,turtles, muskrats, and

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246. *See* Robert Poulin & Serge Morand, *The Diversity of Parasites*, 75 Q. REV. BIOLOGY 277 (2000) (practically all free-living multicellular animals harbor one or more parasite species).

247. Gretchen C. Daily, *Developing a Scientific Basis for Managing Earth's Life Support Systems*, 3 CONSERVATION ECOLOGY (2) 14, *available at* http://www.consecol.org/vol3/iss2/art14 (last visited Sept. 15, 2001) (a substantial portion of biodiversity occurs in human-dominated habitats); Wu & Loucks, *supra* note 129, at 460 (hierarchical patch dynamics emphasizes, rather than avoids, heterogeneity).

248. *See, e.g.*, BROWN, *supra* note 52, at 201.

249.
> In many ways, variability in space and in time is interchangeable . . . . Strategies have evolved to deal with unpredictability; greater predictability may be achieved by averaging over space, through dispersal, or over time, through dormancy or by becoming perennial. Space and time are two different ways for . . . reducing risk while eschewing potentially larger payoffs; evolution is for the long haul.

LEVIN, *supra* note 91, at 74.

250. Holling, *supra* note 139, at 479.

251. Timothy Beatley, *Preserving Biodiversity: Challenges for Planners*, 66 J. AM. PLAN. ASS'N 5, 10-13 (2000).

252. *See* H. Ronald Pulliam, *Sources, Sinks, and Population Regulation*, 132 AM. NATURALIST 652 (1988). *See* NAT'L RESEARCH COUNCIL, *supra* note 227, at 98-99.

253. UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, OFFICE OF FEDERAL ACTIVITIES, CONSIDERING ECOLOGICAL PROCESSES IN ENVIRONMENTAL IMPACT ASSESSMENTS 72 (1999). A metapopulation has been defined as "a population of local populations linked by exchanges of individuals." FARINA, *supra* note 110, at 81.

other wetland animals raise more young than can occupy their home wetland. The young disperse throughout the surrounding area in search of other wetland sites. As long as there are enough wetland sites within dispersal range, a wetland can be recolonized even if the local population goes extinct.[254] The study of the dynamics of movement by individual animals among habitat patches (that are themselves transient) has produced some of the most interesting ecological research in recent years and has created a new subspecialty known as "metapopulation ecology."[255]

Metapopulation ecologists rely heavily on computer models.[256] The models forecast the size and relative location of patches that will be needed to sustain a species of particular dispersal capability.[257] Both metapopulation and landscape ecologists increasingly tend to use the terminology developed by H. Ronald Pulliam, who divides habitats for a particular species into "sources, sinks and traps." Sources are habitats in which the species can reproduce successfully; i.e., where the birth rate is higher than the death rate. Sinks are habitats in which a species can survive, but not thrive, because the death rate exceeds the birth rate, but the species continues to be found in such habitats because young individuals move into the habitat after they leave their parents. Traps are habitats that appear to be suitable breeding sites to the species, but in fact are not. For example, a farmer's hay field may attract nesting birds every year even though the nesting always fails because the hay is cut before the birds fledge.[258]

Do source habitats automatically deserve more protection than sinks?[259] This idea is intuitively appealing, but a habitat that

254. NOSS & COOPERRIDER, *supra* note 194, at 61-62. Not all species exhibit metapopulation behavior. Peggy L. Fiedler et al., *The Paradigm Shift in Ecology and Its Implications*, *in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 83, 99-100 (Steward Pickett et al. eds, 1997).

255. Finnish ecologist Ilkka Hanski has published extensively in this field. *See generally* ILKKA A. HANSKI, METAPOPULATION ECOLOGY (1999).

256. *See generally* Ilkka Hanski, *Metapopulation Dynamics*, 396 NATURE 41 (1998) (reviewing metapopulation modeling studies); METAPOPULATION BIOLOGY: ECOLOGY, GENETICS AND EVOLUTION (Ilkka Hanski & Michael E. Gilpin eds., 1997) (providing an updated survey of emerging metapopulation biology theories.).

257. *See* Ilkka Hanski & Otso Ovaskainen, *The Metapopulation Capacity of a Fragmented Landscape*, 404 NATURE 755 (2000) (proposing model for estimating capacity of patchy habitat to support particular species). *But see* Susan Harrison, *Metapopulations and Conservation*, *in* LARGE-SCALE ECOLOGY AND CONSERVATION BIOLOGY 111,123 (P.J. Edwards et al. eds, 1993) (arguing that metapopulation behavior may apply only to relatively few species).

258. H. Ronald Pulliam, *Sources and Sinks: Empirical Evidence and Population Consequences*, *in* POPULATION DYNAMICS IN ECOLOGICAL SPACE AND TIME 45, 55-56 (Olin E. Rhodes, Jr. et al. eds., 1996). Similar conditions apply to plants, many of which disperse seeds into areas where the plant can persist but not thrive. FARINA, *supra* note 110, at 77-78.

259. *See* A. Townsend Peterson, *Endangered Species and Peripheral Populations: Cause for*

appears to be a sink[260] may be occupied by transient individuals on the way to new source habitats.[261] Also, the study of patch dynamics has made us aware of the extent to which patterns of habitat change over time,[262] so that in many situations, sinks are an important component of spatial structure and contribute to the persistence of species.[263]

Patch dynamics and metapopulation dynamics have raised new questions about the extent to which large areas of undifferentiated habitat are more important for the protection of biodiversity than mosaics of small patches of different habitats.[264] After long debate, by the early 1990s most biologists seemed to agree that preservation of large, contiguous habitats was preferable to preservation of a similar area of land divided into smaller reserves.[265]

Reflection, 18 ENDANGERED SPECIES UPDATE 30, 31 (2001) (future efforts should concentrate on "areas in which probabilities of success are high."). *See also* U.S. EPA, OFFICE OF FED. ACTIVITIES, CONSIDERING ECOLOGICAL PROCESSES IN ENVIRONMENTAL IMPACT ASSESSMENTS 72 (1999) ("Preservation of sink populations alone cannot protect a species.").

260. With many kinds of animals, the problem of identifying which patches are sinks and which are sources is extremely difficult. *See* Scott K. Robinson, *Nest Gains, Nest Losses, in* SCIENTISTS ON BIODIVERSITY 79, 80 (Linda Koebner et al. eds., 1998) (discussing difficulty of correlating predation and brood parasitism records with species population counts).

261. Mark E. Ritchie, *Populations in a Landscape Context: Sources, Sinks and Metapopulations, in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 160, 176, 179-180 (John A. Bissonette ed., 1997). The very definition of habitat depends on how many species are present in an area. More diverse habitats result in more species. But which comes first? At very large geographic scales, "the more species, the more habitats [the biologists] recognize." At smaller scales, it is the variation in habitat that controls. MICHAEL L. ROSENZWEIG, SPECIES DIVERSITY IN SPACE AND TIME 175-76 (1995). "Species discriminate habitats because natural selection forces them to. The more species, the more narrowly they specialize. The more they specialize, the more the ecologist sees different habitats." *Id.* at 189.

262. S.T.A. Pickett & Kevin H. Rogers, *Patch Dynamics: The Transformation of Landscape Structure and Function, in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 101, 102 (John A. Bissonette ed., 1997).

263. Some ecologists suggest that the habitats with the most diversity of species are likely to be sinks. FARINA, *supra* note 110, at 80. MAURER, *supra* note 102, at 152. "Remnant" populations of plants may survive in sinks for long periods of time. Ove Eriksson, *Functional Roles of Remnant Plant Populations in Communities and Ecosystems*, 9 GLOBAL ECOLOGY & BIOGEOGRAPHY 443 (2000).

264. Many of the studies on which the preference for large blocks of similar habitat were based involved studies of forest birds, some of which clearly seem to prefer large areas of deep woods. *See e.g.*, D.M. Burke & E. Nol, *Landscape and Fragment Size Effects on Reproductive Success of Forest-Breeding Birds in Ontario,* 10 ECOLOGICAL APPLICATIONS 1749, 1757 (2000). Recently, a committee of the Ecological Society of America approached this issue cautiously, pointing out that landscape fragmentation does not necessarily destroy ecological functions or decrease biodiversity, and that making a naturally patchy landscape more uniform may have adverse effects, but also concluding that large decreases in the size of habitat patches or increases in the distance between them can reduce biodiversity and alter ecological system processes. Dale et al., *supra* note 47, at 654-55.

265. *See* Ruhl, *supra* note 126, at 966.

The island biogeography theory[266]developed by Robert H. MacArthur and Edward O. Wilson in the 1960s[267] was one of the most influential works on ecology in that period.[268] They proposed a mathematical formula to determine how many species of any given taxa would be found on an island. In general, the number of species increased with the size of the island and the biotic richness of the region and decreased with the distance of the island from sources of immigration.[269]

Ecologists soon began to think that the model applicable to islands could be applied more generally to all sorts of patches of habitat in a heterogeneous environment, and each patch could be treated as an island surrounded by something different.[270] Disconnected mountaintops, for example, might be effectively isolated "islands" because few species could successfully traverse the terrain between them.[271]

Studies of forest birds found that a number of species could successfully reproduce only in large patches of undisturbed forest.[272] It appeared that many forest birds reproduced most successfully if they were a long distance from the edge of the forest. Near the edge of the forest, they were exposed to greater effects of predation and egg substitution by animals such as raccoons and cowbirds that avoided the deep forest.[273] This is often referred to as the "edge effect."[274]

266. For a concise description of island biogeography theory, see A. Schoener, *Experimental Island Biogeography*, *in* ANALYTICAL BIOGEOGRAPHY: AN INTEGRATED APPROACH TO THE STUDY OF ANIMAL AND PLANT DISTRIBUTIONS 483, 487-488 (A.A. Myers & Paul S. Giller eds., 1988). For a discussion of the origins of island biogeography theory, see WORSTER, *supra* note 167, at 375-78. For a thorough analysis of biogeography of islands, see ROBERT J. WHITTAKER, ISLAND BIOGEOGRAPHY: ECOLOGY, EVOLUTION, AND CONSERVATION (1998).

267. ROBERT H. MACARTHUR & EDWARD O. WILSON, THE THEORY OF ISLAND BIOGEOGRAPHY (1967).

268. WHITTAKER, *supra* note 266, at 113-14.

269. *Id.* at 115.

270. MCINTOSH, *supra* note 50, at 280-83.

271. DAVID QUAMMEN, THE SONG OF THE DODO: ISLAND BIOGEOGRAPHY IN AN AGE OF EXTINCTIONS 438-39 (1996). Recent studies of hilltops in Venezuela that became isolated islands when a new dam created a large reservoir have illustrated the serious loss of biodiversity that such isolation can create. John Terborgh et al., *Ecological Meltdown in Predator-Free Forest Fragments*, 294 SCI. 1923 (2001). *See also* Jared Diamond, *Dammed Experiments!*, 294 SCI. 1847 (2001).

272. The classic study is Chandler S. Robbins et al., *Habitat Area Requirements of Breeding Forest Birds of the Middle Atlantic States,* 103 WILDLIFE MONOGRAPHS 1 (1989). For an example of a recent study, see Christine A. Howell et al., *Landscape Effects Mediate Breeding Bird Abundance in Midwestern Forests,* 15 LANDSCAPE ECOLOGY 547 (2000).

273. ROBERT A. ASKINS, RESTORING NORTH AMERICA'S BIRDS: LESSONS FROM LANDSCAPE ECOLOGY 110-16 (2000).

274. Hendrik Andrén, *Effects of Landscape Composition on Predation Rates at Habitat Edges, in* MOSAIC LANDSCAPES AND ECOLOGICAL PROCESSES 225, 225 (Lennart Hansson et al. eds., 1995).

The similarity of a fragmented forest to islands in a sea led to attempts to apply island biogeography theory to forests. Much of the concern over habitat fragmentation grows out of studies showing that many species of birds and large predators are dependent on relatively large blocks of forest in order to reproduce.[275] This fear of expanding edge effects led many conservation biologists to prefer protection of large, undifferentiated habitats rather than heterogeneous mixtures of habitat patches.[276]

In *Sierra Club v. Marita*,[277] the Sierra Club sought to convince the federal courts that large areas of homogeneous forest are always better biologically than smaller patches. The case involved the adoption of forest management plans for two national forests in northern Wisconsin.[278] The court of appeals was unconvinced and deferred to the United States Forest Service's opinion that the merits of large homogeneous forests were not clearly established.[279] Was the Sierra Club's argument that larger reserves are always better scientifically sound?

Some species of forest birds may spend all of their lives in the dense forest and depend solely upon it, but many others rely not only on the forest but also on other types of habitat, moving between different habitats as they feed, breed, and seek shelter.[280] Ecotones – the boundaries between different types of habitat – are generally characterized by high biological diversity.[281] Ecologists increasingly recognize that ecotones are important zones in their

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275. *See, e.g.*, D.M. Burke & Erica Nol, *Landscape and Fragment Size Effects on Reproductive Success of Forest-breeding Birds in Ontario*, 10 ECOLOGICAL APPLICATIONS 1749, 1757 (2000); Gretchen C. Daily et al., *Countryside Biogeography: Use of Human-dominated Habitats by the Avifauna of Southern Costa Rica*, 11 ECOLOGICAL APPLICATIONS 1 (2001) (reporting that at least half of the bird species of Southern Costa Rica seem to have no prospects for survival outside of the forest).

276. *See, e.g.*, RICKLEFS, *supra* note 58, at 610; Bradley C. Karkkainen, *Biodiversity and Land*, 83 CORNELL L. REV. 1, 11-14 (1997) (describing broad but not universal consensus on protection of large reserves connected by corridors).

277. 46 F.3d 606 (7th Cir. 1995).

278. *Id.* at 608-09.

279. *Id.* at 619-24.

280. Pickett & Rogers, *supra* note 116, at 101, 104 (Organisms may require a "commodious mixture of . . . patch types" at various stages of their life cycle or at different seasons of the year). Where dispersal rates are particularly high, many singleton species will be found in sink conditions, and the richness of species in the area will seem abnormally high. HUBBELL, *supra* note 39, at 315-16.

281. VEGETATION MAPPING FROM PATCH TO PLANET, *supra* note 13, at 328 (noting increasing recognition that habitat zones have fuzzy edges). *See also* Marjorie M. Holland & Paul G. Risser, *Introduction to* ECOTONES: THE ROLE OF LANDSCAPE BOUNDARIES IN THE MANAGEMENT AND RESTORATION OF CHANGING ENVIRONMENTS 1 (Marjorie M. Holland et al. eds., 1991). In the western United States, grazing may increase local biodiversity in some areas but may be reducing biodiversity at larger scales. DEBRA L. DONAHUE, THE WESTERN RANGE REVISITED: REMOVING LIVESTOCK FROM PUBLIC LANDS TO CONSERVE NATIVE BIODIVERSITY 163-69 (1999).

own right and can no longer be treated merely as lines on a map.[282] Connecticut College ecologist Robert Askins notes that the fragmentation of Eastern forests may provide some biodiversity benefits by creating good habitat for shrubland birds, such as Yellow-breasted chats, White-eyed vireos, and Chestnut-sided warblers, whose numbers are declining.[283]

Most ecologists today believe that "the debate about the effectiveness of a single large reserve as opposed to several small ones is far from being resolved."[284] In general, the larger the area one looks at, the more species it is likely to have, regardless of the degree of heterogeneity.[285] University of Arizona biologist Michael Rosenzweig points out that if area is kept equal, studies show that "species diversity rises with habitat diversity."[286] More recent metapopulation theories have emphasized the important role that discontinuous patches may play in protecting species from the impact of widespread epidemic or conflagration.[287] Forest diversity is enhanced when a variety of successional stages are represented. For example, when a storm or the death of a large tree opens a new

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282. M.-J. Fortin et al., *Issues Related to the Detection of Boundaries*, 15 LANDSCAPE ECOLOGY 453, 462 (2000) (suggesting that more sophisticated mapping of ecotones is needed).

283. ASKINS, *supra* note 273, at 48-49. Recent studies suggest that in North America the birds that occupy disturbed habitats have suffered greater population declines than the species that occupy mature forests. This is assumed to be the result of fire and flood suppression. Jeffrey D. Brawn, *The Role of Disturbance in the Ecology and Conservation of Birds*, 32 ANN. REV. ECOLOGY & SYSTEMATICS 251 (2001). The development of ecological models that predict the impact of fragmentation of plants and animals has proven to be difficult. *See, e.g.*, S.A. Bailey et al., *Habitat Fragmentation in England's Ancient Woods: Implications for Managing Biodiversity*, *in* HETEROGENEITY IN LANDSCAPE ECOLOGY 225 (M.J. Maudsley & E.J.P. Marshall eds., 1999).

284. NAT'L RESEARCH COUNCIL, *supra* note 227, at 136. Advances in computational ability and model design are now beginning to make it possible to combine metapopulation models with patch dynamic models; one such study concluded that the size of a reserve area may be of less importance than its degree of persistence over time. Juan E. Keymer et al., *Extinction Thresholds and Metapopulation Persistence in Dynamic Landscapes*, 156 AMERICAN NATURALIST 478, 490 (2000). *See also* JAMES H. BROWN & MARK V. LOMOLINO, BIOGEOGRAPHY 565 (2d ed. 1998) (reporting that science cannot definitively say whether large or small reserves are better).

285. MICHAEL A. HUSTON, BIOLOGICAL DIVERSITY: THE COEXISTENCE OF SPECIES ON CHANGING LANDSCAPES 35 (1994).

286. ROSENZWEIG, *supra* note 261, at 210 (but not on islands, where other variables need to be considered *Id.* at 263). *See also* Pickett & Rogers, *supra* note 116, at 107 (holding that patchiness contributes to biodiversity).

287. Ilkka Hanski & Daniel Simberloff, *The Metapopulation Approach: Its History, Conceptual Domain, and Application to Conservation*, *in* METAPOPULATION BIOLOGY: ECOLOGY GENETICS AND EVOLUTION 5, 20-21 (Ilkka Hanski & Michael E. Gilpin eds., 1997). The authors say that there has been a "paradigm shift" away from island biogeography to metapopulation theory (*Id.* at 16-19), but that the cost of metapopulation studies has often proved to be too great for ecosystem management programs (*Id.* at 26); David J.D. Earn et al., *Coherence and Conservation*, 290 SCI. 1360 (2000) (proposing model to test whether corridors connecting habitat patches are helpful or harmful.). *See also* NAT'L RESEARCH COUNCIL, *supra* note 227, at 101.

patch in the forest, it then receives more sunlight and becomes populated with new species. As that patch gets older, another new patch forms elsewhere, so that the "natural forest becomes a tapestry of patches in different stages of succession, and hence a tapestry of diversity."[288]

The forests of northern Wisconsin were not homogeneous in their natural state: "Contrary to romantic imagination, Wisconsin's forests before Anglo-American settlement were not one ideal homogeneous stand of virgin white pine stretching across its expanse. In reality, Wisconsin's 'true' forest was neither 'piney' nor 'virgin.'" It was "ever-evolving and changing, differing in geology, soil conditions, disease, insects, windfalls, natural forest fires, and simply old age."[289] Today, more sophisticated studies of heterogeneous habitats view the island analogy as "superficial."[290] In terrestrial environments, the matrix (i.e., the spaces surrounding the patches) cannot be treated as a black hole in the way the ocean is treated in island biogeography models. As one ecologist recently put it, "the matrix matters."[291]

So is the preference for large habitat patches misguided? The distinguished British biologist Robert May says "[t]here is no doubt that the diversity of life on earth would be less if terrestrial and marine environments were significantly more homogeneous than they are."[292] Where a metapopulation of a species is distributed among many patches, and there is opportunity for movement among the patches, the risk that predation, disease, or some unpredictable environmental event will cause the extinction of the entire population is substantially reduced.[293] Thus, for species with

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288. LEVIN, *supra* note 91, at 88. *See, e.g.*, David B. Lindenmayer et al., *Effects of Forest Fragmentation on Bird Assemblages in a Novel Landscape Context*, 72 ECOLOGICAL MONOGRAPHS 1 (2002) (large scale study of eucalyptus forests in Australia shows that forest patches of all sizes have significant conservation value because some native species are more abundant in smaller patches).

289. ANTHONY GODFREY, A FORESTRY HISTORY OF TEN WISCONSIN INDIAN RESERVATIONS UNDER THE GREAT LAKES AGENCY: PRECONTACT TO PRESENT 4 (1996).

290. "The superficial similarities between oceanic islands and community fragments mask fundamental differences in history, age, internal habitat conditions, and surrounding matrices." Martin Kellman, *Redefining Roles: Plant Community Reorganization and Species Preservation in Fragmented Systems*, 5 GLOBAL ECOLOGY AND BIOGEOGRAPHY LETTERS 111, 111 (1996).

291. Taylor H. Ricketts, *The Matrix Matters: Effective Isolation in Fragmented Landscapes*, 158 AM. NATURALIST 87 (2001).

292. Robert M. May & T R.E. Southwood, *Introduction to* LIVING IN A PATCHY ENVIRONMENT 1, 13-14 (Bryan Shorrocks & Ian R. Swingland eds., 1990). "At landscape scales spatial heterogeneity, or patchiness, in the environment offers the possibility of regional coexistence in spite of local extinction." HUSTON, *supra* note 285, at 88.

293. May & Southwood, *supra* note 292, at 6. Metapopulation theories have led to a burst of empirical research on the dispersal abilities of various species. *See, e.g.*, Niklas Wahlberg et al., *Metapopulation Structure and Movements in Five Species of Checkerspot Butterflies*,

good dispersal capabilities, increased habitat fragmentation may reduce the risk of extinction.[294]

There is no doubt that the destruction of huge tracts of tropical forest is driving to extinction many species, undoubtedly including some that will never have been identified.[295] So little is known about the ecology of tropical forests that scientists fear that logging and burning will destroy unique attributes of the forest before we fully understand them.[296] But the problems are caused by the vast scale of forest destruction, rather than by fragmentation.[297] Many ecologists view deforestation as "largely a tropical issue,"[298] although the logging of the old growth forests of the Northwestern United States has also been very controversial.[299] I do not mean to minimize the importance of deforestation, which has implications for climate as well as biodiversity, but I believe it is inappropriate to characterize it as a fragmentation problem.

Isolated fragments of landscape elements are often critical habitats for rare species.[300] For example, in the Southern

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130 OECOLOGIA 33 (2002).

294. Mark E. Ritchie, *Populations in a Landscape Context: Sources, Sinks and Metapopulations, in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 160, 172-75, 181 (John A. Bissonette ed., 1997). *See* HUBBELL, *supra* note 39, at 228. (suggesting the impact of fragmentation is primarily in its effect on mean dispersal rates). "[O]ne can predict both the species richness and relative species abundance in a metacommunity undergoing zero-sum ecological drift" from the "area and the average speciation rate in the biogeographic region, the density of organisms per unit area, and . . . the mean dispersal rate of species over the landscape." *Id.* at 149.

295. T. C. Whitmore, *Tropical Forest Disturbance, Disappearance, and Species Loss, in* TROPICAL FOREST REMNANTS: ECOLOGY, MANAGEMENT, AND CONSERVATION OF FRAGMENTED COMMUNITIES 3, 11 (William F. Laurance & Richard O. Bierregaard, Jr. eds., 1997). In addition to the adverse impact on biodiversity, tropical forest destruction is aggravating the trend toward global warming. NAT'L RESEARCH COUNCIL, *supra* note 7, at 48.

296. In the last 50 years, 9,000,000 square kilometers of tropical forest have been lost. Stuart L. Pimm et al., *Can We Defy Nature's End?*, 293 SCI. 2207, 2207 (2001). For a concise summary of the problems of fragmentation of tropical forests, see William F. Laurence et al., *Tropical Forest Fragmentation: Synthesis of a Diverse and Dynamic Discipline, in* TROPICAL FOREST REMNANTS: ECOLOGY, MANAGEMENT, AND CONSERVATION OF FRAGMENTED COMMUNITIES 502 (William F. Laurance & Richard O. Bierregaard, Jr. eds., 1997).

297. EDWARD O. WILSON, THE FUTURE OF LIFE 58-66 (2002); Osvaldo E. Sala et al., *Global Diversity Scenarios for the Year 2100*, 287 SCI. 1770-71 (2000). *See generally* K.D. Singh, *Rainforest Loss and Change, in* 5 ENCYCLOPEDIA OF BIODIVERSITY 25 (Simon A. Levin ed., 2001).

298. Jaboury Ghazoul & Julian Evans, *Deforestation and Land Clearing, in* 2 ENCYCLOPEDIA OF BIODIVERSITY 23, 35 (Simon A. Levin ed., 2001). *See also* G. Arturo Sânchez-Azofeifa et al., *Deforestation in Costa Rica: A Quantitative Analysis Using Remote Sensing Imagery*, 33 (3) BIOTROPICA 378 (2001).

299. *See generally* R. EDWARD GRUMBINE, GHOST BEARS: EXPLORING THE BIODIVERSITY CRISIS (1992).

300. Mark E. Ritchie, *Populations in a Landscape Context: Sources, Sinks and Metapopulations, in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 160, 181 (John A. Bissonette ed., 1997) (noting that species that prefer rare habitats are more likely to go extinct).

Appalachians, 84% of the federally listed species occur in rare habitat communities.[301] The retention of even small, apparently relict fragments of lost landscapes may be important as source material if future environmental changes make it possible to recreate earlier conditions.[302] Many ecologists believe that insufficient attention is being paid to the management needs of such fragments.[303]

On the other hand, where human activities have reduced natural habitats to small patches, the adverse impact on ecological systems can be severe.[304] In much of the Florida landscape, for example, the habitat fragments may be too small to support either closed-canopy forest species that need to be a substantial distance from the edge of the habitat or wide-ranging species such as the Florida panther.[305] Small reserves increase our need to create connecting corridors[306] and to be prepared to reintroduce predators into the system, because species at the top of the food chain may be at great risk of localized extinction as the size of habitats diminish, and such species may be essential for the protection of the ecological system.[307]

No one is arguing that fragmentation is always desirable, but current research makes it apparent that the blanket condemnation of fragmentation that still appears in much of the conservation biology literature[308] needs to be replaced by a more nuanced look at the pros and cons of large and small habitat patches in particular situations.[309]

C. Disturbance of Ecological Systems Doesn't Always Mean Destruction

Ecological change caused by natural disturbance is not only inevitable but, within limits, necessary if ecological processes are to be maintained. This current view is a departure from much of the

301. Dale et al., *supra* note 47, at 659.

302. ASKINS, *supra* note 273, at 235-36. *See also* Kellman, *supra* note 290, at 114 (suggesting that extreme fragmentation may be a temporary phenomenon).

303. Kellman, *supra* note 290, at 111-12.

304. U.S. EPA, *supra* note 227, at 17-18. *See, e.g.*, Jennifer J. Swenson & Janet Franklin, *The Effects of Future Urban Development on Habitat Fragmentation in the Santa Monica Mountains*, 15 LANDSCAPE ECOLOGY 713 (2000) (modeling edge effects of various urban development patterns).

305. Harris, *supra* note 172, at 337-38. *See also* Reed F. Noss, *Protecting Natural Areas in Fragmented Landscapes*, 7 NAT. AREAS J. 2, 3 (1987).

306. *See generally* ANDREW F. BENNETT, LINKAGES IN THE LANDSCAPE: THE ROLE OF CORRIDORS AND CONNECTIVITY IN WILDLIFE CONSERVATION (IUCN 1999).

307. ROSENZWEIG, *supra* note 261, at 383.

308. *See, e.g.*, ANDREW P. DOBSON, CONSERVATION AND BIODIVERSITY 33-57 (1996).

309. NAT'L RESEARCH COUNCIL, *supra* note 7, at 50.

earlier ecological thinking, which endorsed the idea of a natural succession of types of species that would each occupy an area in turn, leading up to a climax condition that represented equilibrium – with the result leading to realization of the ancient religious belief in a "balance of nature."[310]

1. The Impermanence of Climax Communities

Frederic Clements, the most prominent ecologist of the early twentieth century, posited that each piece of the landscape had a natural condition of "equilibrium" that it would achieve if left alone.[311] Clements wrote extensively about natural processes by which one plant community is replaced by another in successive waves.[312] He noted that certain pioneer species were adept at moving into new environments and multiplying rapidly,[313] but they would eventually be replaced ("succeeded") by more long-lived species that would eventually form the "climax" community when a state of "equilibrium" was reached.[314] Each plant and animal species would then occupy its niche permanently.[315]

For example, in the central United States, Clements described how an area of bare sand would become colonized by cottonwoods, which would be replaced by jack pines growing up in the shade of the cottonwoods, which then would be replaced by black oaks, white oaks, and red oaks in turn, which would finally give way to the climax forest of beech and maple.[316] Of course, the forest might be disturbed by fire, insect epidemic, or other natural event,[317] but in

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310. The scientific acceptance of the idea that a "balance of nature" exists can be traced back to the great Swedish systematist, Carl von Linné, known as Linnaeus, whose eighteenth-century treatise was widely admired. CARL VON LINNÉ, THE OECONOMY OF NATURE (1749). Linnaeus postulated that the Creator had devised a perfectly static world in which the relationships of every living creature were in balance with each other and their surroundings. WORSTER, *supra* note 167, at 35-36. Ecologists were sometimes criticized for unrealistic assumptions about a balanced nature. *See, e.g.*, PETER ROGERS, AMERICA'S WATER: FEDERAL ROLES AND RESPONSIBILITIES 81 (1993) ("The theories underlying the ecological approach to natural resources policies rely heavily on scientific analyses of individual components pieced together with a not altogether scientifically defensible idea of nature's balance.").

311. Frederic E. Clements, *Nature and Structure of the Climax*, 24 J. ECOLOGY 252, 256 (1936).

312. *See e.g.*, JOHN WEAVER & FREDERIC E. CLEMENTS, PLANT ECOLOGY 60-79 (2d ed. 1938).

313. For a summary of Clements' ideas about succession, see KREBS, *supra* note 154, at 483-85.

314. Clements, *supra* note 311, at 255-56.

315. KREBS, *supra* note 154, at 483-85.

316. *See* WEAVER & CLEMENTS, *supra* note 312.

317. Norman Christensen suggests that a century ago, management of wilderness preserves was "seen as operationally equivalent to museum curation on a grand scale." Christensen, *supra* note 172, at 175. Clements and others viewed fire and other disturbances as negative events that prevented ecosystems from attaining or maintaining their climax

the long run it wouldn't matter because the process of succession would begin again and the habitat eventually return to the climax condition.[318]

Over time, ecologists increasingly began to question the validity of the ideas of equilibrium and the balance of nature. By the 1970s, extended critiques of the concept of equilibrium had begun to appear.[319] In the 1980s, a new paradigm began to be discussed.[320] One of its earliest proponents, Steward Pickett, argued that the processes by which ecological systems undergo change are an essential element of the ecological systems' makeup. "Thus, rather than viewing ecosystems as being 'in balance,' systems are seen as in flux . . . ."[321] University of Illinois wildlife law expert Eric Freyfogle summarizes the importance of this change:

> Ecologists now realize that the whole concept of community climax is misleading, for climaxes are always tentative and subject to being upset by a wide variety of natural forces, including fire, disease, and weather. In the north woods, white pine is vulnerable to fire and disease, and when it dies, it opens the way for the jack pine and birch to return. This disease- or fire-driven transition from white pine to jack pine and birch is as natural as the shift onward to balsam and spruce. Animal populations, too, experience wide fluctuations, and in the long

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state. *See* FREDERIC E. CLEMENTS & VICTOR E. SHELFORD, BIO-ECOLOGY 248 (1939) (noting that climax may persist for thousands of years).

318. "While the climax is permanent because of its entire harmony with a stable habitat, the equilibrium is a dynamic one and not static. Superficial adjustments occur with the season, year, or cycle . . . . While change is constantly and universally at work, in the absence of civilized man this is within the fabric of the climax and not destructive of it." WEAVER & CLEMENTS, *supra* note 312, at 80. For a concise summary of the origins of equilibrium theory, see Wu & Loucks, *supra* note 129, at 441-43.

319. *See, e.g.*, Peter S. White, *Pattern, Process, and Natural Disturbance in Vegetation*. 45 BOTANICAL REV. 229, 231 1979) (suggesting that the importance of ongoing dynamics is difficult to reconcile with the idea of equilibrium). For a discussion of the early history of the recognition of the importance of dynamics in ecology, see Donald Worster, *The Ecology of Order and Chaos, in* OUT OF THE WOODS: ESSAYS IN ENVIRONMENTAL HISTORY 3, 9-11 (Char Miller & Hal Rothman eds., 1997).

320. For a history of the development of the nonequilibrium paradigm, see Peggy L. Fiedler et al., *The Paradigm Shift in Ecology and Its Implications for Conservation, in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 83, 84-87 (Steward T.A. Pickett et al. eds, 1997).

321. V. Thomas Parker & Steward T.A. Pickett, *Restoration as an Ecosystem Process: Implications of the Modern Ecological Paradigm, in* RESTORATION ECOLOGY AND SUSTAINABLE DEVELOPMENT 17, 22 (Krystyna M. Urbanska et al. eds, 1997) (noting that ecosystems are open, can be regulated by external processes, and are subject to natural disturbances.)

> run, climatic changes bring even greater alterations. The idea of the climax having lost much of its explanatory force, ecologists today speak about nature in terms that are far more fluid. Some species are expanding their range at any time, while others are contracting. New forms are emerging, particularly at the microscopic level. Images of conflict have yielded to more mixed images that include large doses of symbiosis and cooperation.[322]

My colleague, Dan Tarlock, has chronicled how this new focus on the tendency of natural areas to change over time has become the key element of "nonequilibrium" ecology,[323] a theory that contrasts sharply with earlier ideas of a "balance" of nature.[324] The basic premise of nonequilibrium ecology has become widely accepted by mainstream ecologists, as exemplified by the report of a committee of the Ecological Society of America: "Ecological processes function at many time scales, some long, some short; and ecosystems change through time."[325] These changes follow patterns that are predictable only at broad landscape levels.[326] The idea that ecological systems are fluid networks[327] that change and interrelate in cyclical fashion has suggested to many ecologists that their science should emphasize the identification and analysis of these cycles in an attempt to build a four dimensional picture of the natural environment.[328]

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322. ERIC T. FREYFOGLE, JUSTICE AND THE EARTH: IMAGES FOR OUR PLANETARY SURVIVAL 129-30 (1993).

323. A. Dan Tarlock, *The Nonequilibrium Paradigm in Ecology and the Partial Unraveling of Environmental Law*, 27 LOY. L.A. L. REV. 1121 (1994).

324. *See generally* Jonathan Baert Wiener, *Beyond the Balance of Nature*, 7 DUKE ENVTL. L. & POL'Y F. 1 (1996).

325. Dale et al., *supra* note 47, at 639.

326. LEVIN, *supra* note 91, at 128 ("Environmental change is constantly shifting the background against which selection is taking place; thus, adaptation occurs on a landscape that is in a perpetual state of oscillation, with peaks dissolving into valleys and new peaks arising from former valleys."). *See generally* DAVID J. MERRELL, THE ADAPTIVE SEASCAPE: THE MECHANISM OF EVOLUTION 137 (1994) (using a stormy sea as the metaphor for the constantly shifting landscape).

327. JIM SANDERSON & LARRY D. HARRIS, LANDSCAPE ECOLOGY: A TOP-DOWN APPROACH 23 (2000) ("An ecosystem is an entity that consists of an abiotic and biotic community that are linked together by the flow of energy through the subentities and the cycling of resources such as water and nutrients.").

328. John A. Wiens, *Metapopulation Dynamics and Landscape Ecology*, *in* METAPOPULATION BIOLOGY: ECOLOGY, GENETICS AND EVOLUTION 43, 47 (Ilkka Hanski & Michael E. Gilpin eds., 1997) ("Elements in a landscape mosaic (patches) vary in quality in both space and time.").

The increasing emphasis on the variability and instability of nature has not been without controversy.[329] Conservation biologists realize that they must challenge the public's notion of a static nature and work toward developing ways for resolving potentially conflicting environmental goals in a variable world.[330]

2. The Irregularity of Succession

Perhaps the most significant change stemming from nonequilibrium ecological theory is its new emphasis on the important role that disturbance, such as wildfire, flood, or epidemic, plays in ecological processes.[331] Contemporary ecology takes the position that, given the proper perspective, those things our society has called "natural disasters" (and ecologists refer to as "disturbances" or "perturbations") are not external to the ecological system but are a vital part of it.[332] Viewed at the proper scale, disturbance can be seen as a necessary ecological process and a stabilizing factor[333] that needs to be understood.[334]

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329. *See* Donald Worster, *The Ecology of Order and Chaos, in* OUT OF THE WOODS: ESSAYS IN ENVIRONMENTAL HISTORY 3, 11-13 (Char Miller & Hal Rothman eds., 1997). Those who believe that internal disagreement within a field of study is a sign of intellectual weakness may wish to read philosopher Mark Sagoff's extensive diatribe against the entire field of scientific ecology. Mark Sagoff, *Muddle or Muddle Through? Takings Jurisprudence Meets the Endangered Species Act*, 38 WM. & MARY L. REV. 825, 953 (1997) ("If all that ecosystems offer is a blooming, buzzing confusion of phenomena with no inherent order or direction, then historical narration and the rules of induction exhaust the theoretical armamentarium of ecological science.").

330. Mark W. Schwartz, *Conflicting Goals for Conserving Biodiversity: Issues of Scale and Value*, 14 NAT. AREAS J. 213, 215 (1994). For a perceptive evaluation of current thinking in nonequilibrium ecology as applied by practicing conservation groups, see WILLIAM HOLLAND DRURY, JR., CHANCE AND CHANGE: ECOLOGY FOR CONSERVATIONISTS (1998).

331. Steward T.A. Pickett and P.S. White produced the pioneering synthesis of the important role of disturbance in ecology in 1985. THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS (Steward T.A. Pickett & P.S. White eds., 1985). For current confirmation of this thesis, see Dale et al., *supra* note 47, at 653 ("The type, intensity and duration of disturbance shape the characteristics of populations, communities, and ecosystems.").

332. *See, e.g.*, Peter R. Grant et al., *Effects of El Niño Events on Darwin's Finch Productivity*, 81 ECOLOGY 2442 (2000) (noting that finches in the Galapagos breed prolifically in El Niño years, but they also take into account the length of time since the last similar event. "Thus perturbations of natural systems can be fully understood only in a broad temporal context."). *See also* Anthony W. King, *Hierarchy Theory: A Guide to System Structure for Wildlife Biologists, in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 185, 208 (John A. Bissonette ed., 1997) (suggesting that occasional collapse of a population may be found normal if viewed from a long time frame).

333. R.V. O'NEILL ET AL., A HIERARCHICAL CONCEPT OF ECOSYSTEMS 163-169 (1986); LEVIN, *supra* note 91, at 112 (1999) ("Local variability and heterogeneity provide the material for change." "[D]isturbance and renewal . . . maintain the diversity.")

334. The U.S. EPA recommends that analysis of any ecological system should include an analysis of its "disturbance regime." U.S. EPA, *supra* note 227, at 24-30.

Although disturbance is now understood to be a key element of ecological dynamics, rather than a temporary interruption of equilibrium, the study of disturbance remains at an early stage. University of Florida ecologist Crawford Holling has been one of the most eloquent exponents of the importance of the study of disturbance. Holling argues that because disturbance is a natural part of ecological cycles, ecological sustainability depends on "the capacity to renew after disturbance." It "is the processes of death and renewal rather than those of birth and growth that lie at the heart of sustainability and diversity."[335] Holling finds that many ecological systems exhibit a four-stage cycle, consisting of the two classic stages of Clements' original theory: (1) colonization, in which rapidly reproducing species move in to take over vacant niches, and (2) conservation, in which the colonizing species are joined by and eventually dominated by what Clements called the "climax community."[336] To these traditional phases Holling adds (3) release, which takes place when the climax stage is so dependent on conditions remaining constant that it becomes "brittle," inviting disturbance, such as disease or exotic species invasion. This disturbance is followed by (4) reorganization, in which the ecological system may return to something approximating its earlier state, stabilize in an alternate state,[337] or collapse.[338]

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335. C.S. Holling, *Biodiversity in the Functioning of Ecosystems: An Ecological Synthesis*, *in* BIODIVERSITY LOSS: ECONOMIC AND ECOLOGICAL ISSUES 44, 60-61 (Charles Perrings et al. eds., 1995). As the renowned ornithologist Alexander Skutch puts it, death may be needed to give species adaptability. "Perhaps, in the long history of the living world, species composed of potentially immortal individuals arose, only to become extinct because they lacked the flexibility that death and mutability give a species to adjust to changing conditions." ALEXANDER SKUTCH, HARMONY AND CONFLICT IN THE LIVING WORLD 30 (2000). The most recent collection of work by Holling and his colleagues is PANARCHY: UNDERSTANDING TRANSFORMATIONS IN HUMAN AND NATURAL SYSTEMS (Lance H. Gunderson & C. S. Holling eds., 2002).

336. KREBS, supra note 154, at 485.

337. C.S. Holling et al., *Science, Sustainability and Resource Management, in* LINKING SOCIAL AND ECOLOGICAL SYSTEMS: MANAGEMENT PRACTICES AND SOCIAL MECHANISMS FOR BUILDING RESILIENCE 342, 350-52 (Fikret Berkes et al. eds., 1998). The idea of alternate stable states appears to be conjectural. *Compare* Alan A. Berryman et al., *Metastability of Forest Ecosystems Infested by Bark Beetles,* 26 RESEARCHES ON POPULATION ECOLOGY 13, 20 (1984) *with* Johan van de Koppel & Peter M. J. Herman, *Do Alternate Stable States Occur in Natural Ecosystems? Evidence from a Tidal Flat,* 82 ECOLOGY 3449 (2001).

338. Ecologists use a variety of terms to describe the situation in which an ecological system no longer is able to perform its earlier functions, including "collapse" (Mary E. Power & David Tilman, *Challenges in the Quest for Keystones,* 46 BIOSCIENCE 609, 616 (1996)), "flip" (EDWARD B. BARBIER ET AL., PARADISE LOST: THE ECOLOGICAL ECONOMICS OF BIODIVERSITY 26 (1994)), and "breakdown" (Holling et al., *supra* note 337, at 350)). For example, destructive changes to some Western grasslands caused by climate change and overgrazing may already have caused collapse by crossing a threshold to a new ecological state that could not easily be reversed even if grazing were ended. DONAHUE, *supra* note 281, at 145-46; Joseph M. Feller & David E. Brown, *From Old-Growth Forests to Old-Growth Grasslands:*

Duke University ecologist Norman Christensen has emphasized that the limited predictability of such disturbances is a key to the study of them. "Patterns of change are neither perfectly cyclic or linear. Rather successional transitions are often complex and patterns of disturbance and recovery are often greatly affected by 'chance' events, that is, phenomena such as variations in weather that are controlled by factors external to the system being managed."[339]

In contrast to Clements' traditional theory that an area would gradually return to a specific climax condition after disturbance,[340] Holling and many other contemporary ecologists see post-disturbance renewal as a new and highly variable stage of the cycle that can most appropriately be described as reorganization.[341] Some disturbances can carry the ecological system into "quite different stability domains – for example, fire can transform mixed grass and tree savannas into shrub dominated semideserts . . . ."[342] But in other cases, disturbance may be necessary to maintain

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Managing Rangelands for Structure and Function, 42 ARIZ. L. REV. 319, 324 (2000). The opposite of collapse is sometimes referred to as the "health" or "integrity" of an ecological system, but the criteria for defining such conditions remain amorphous. Eric T. Freyfogle, *Illinois Life and an Environmental Testament*, 1997 U. ILL. L. REV. 1081, 1086 (1997). *See, e.g.*, Giulio A. De Leo & Simon A. Levin, *The Multifaceted Aspects of Ecosystem Integrity*, 1 CONSERVATION ECOLOGY 1997, *available at* www.consecol.org/vol1/iss1/art3 (preferring integrity to health as an appropriate concept). "Biological integrity" has sometimes been used to mean the capacity to support the full range of elements and process expected in the natural habitat of the region. NAT'L RESEARCH COUNCIL, *supra* note 3, at 24.

339. Christensen, *supra* note 172, at 178. In his critique of Clements' succession theory, Holling makes four key points: (1) invasion of persistent species during succession can be highly probabilistic; (2) both early and late successional species can be present continuously; (3) disturbances are an inherent part of the internal dynamics, and, in many cases, set the timing of successional cycles; and (4) some disturbances can severely and permanently disrupt the stability of the ecological system. Holling, *supra* note 139, at 480-81. The divergence of emphasis between stability and change can be traced back to the Greek philosophers, Heraclitus and Parmenides. Stan Godlovitch, *Things Change: So Whither Sustainability*, 20 ENVTL. ETHICS 291 (1998).

340. For a summary of Clements' contributions to ecology, see ROBERT P. MCINTOSH, THE BACKGROUND OF ECOLOGY: CONCEPT AND THEORY 42, 43 (1985). The idea of equilibrium still has its supporters, and in appropriate situations it can serve as a baseline for ecological studies. *See, e.g.*, Stuart L. Pimm, *The Complexity and Stability of Ecosystems*, 307 NATURE 321 (1984); Michael G. Neubert & Hal Caswell, *Alternatives to Resilience for Measuring the Responses of Ecological Systems to Perturbations*, 78 ECOLOGY 653 (1997).

341. Species that invade a disturbed area may be highly variable and determined by chance events, and might include what have traditionally been labeled both early and late successional species. Or disturbance can create conditions that favor completely new species that change the basic character of the ecological system. Holling, *supra* note 139, at 481.

342. C.S. Holling, *Biodiversity in the Functioning of Ecosystems, in* Biodiversity Loss: Economic and Ecological Issues 44, 60-61 (Charles Perrings et al. eds.,1992) (citing Mount St. Helens example). For a discussion of the reorganization of the ecological systems after the Mount St. Helens eruption, see Monica G. Turner & Virginia H. Dale, *Fires, Hurricanes, and Volcanoes: Comparing Large Disturbances*, 47 BIOSCIENCE 758 (1997).

existing ecological processes.[343] The study of ecological systems at large space and time scales is advancing our knowledge of the role that disturbance plays in particular habitats.[344]

i. Patterns in Space: The Example of Coral Reefs

Coral reefs are among the most diverse[345] and productive ecological systems in the ocean[346] and are particularly sensitive to impacts from human activities because they depend on clear water to process sunlight.[347] They have long been thought the most confusing and unpredictable of ecological systems.[348]

Today, remote sensing has enhanced scientists' ability to study and compare coral reefs on a worldwide scale.[349] Increasingly, this research has disclosed patterns in what was formerly just confusion.[350] One such pattern that has aroused worldwide concern is what appears to be a widely observed decline of coral reef habitat quality.[351] For example, the extensive coral reef system around Jamaica has been largely destroyed.[352] Although the use of onshore

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343. *See* discussion *infra* notes 419-31.

344. *See, e.g.*, Thomas Brooks & Michael Leonard Smith, *Caribbean Catastrophes*, 294 SCIENCE 1469 (2001) (pointing out that large scale disturbance may have very different ecological impact than repeated small scale disturbances).

345. The phyletic diversity of coral reefs vastly exceeds that of any other habitat on earth. Of the 34 animal phyla, 32 are found on coral reefs. James W. Porter & Jennifer I. Tougas, *Reef Ecosystems: Threats to their Biodiversity*, *in* 5 ENCYCLOPEDIA OF BIODIVERSITY 73, 75 (Simon A. Levin ed., 2001). *See also* PETER F. SALE, THE ECOLOGY OF FISHES ON CORAL REEFS 4 (1991) ("The hundreds, or sometimes thousands, of species of fish present on a coral reef make these as rich or richer than any other environment for fish on earth.").

346. "Complex and productive, coral reefs boast hundreds of thousands of species, many of which are undescribed by science. They are renowned for their beauty, biological diversity and high productivity." Ove Hoegh-Guldberg, *Climate Change, Coral Bleaching and the Future of the World's Coral Reefs*, 50 MARINE & FRESHWATER RESEARCH 839 (1999).

347. U.S. EPA, OFFICE OF WATER, NATIONAL WATER QUALITY INVENTORY: 1998 REPORT TO CONGRESS 120 (1998).

348. Robert M. May, *The Effect of Spatial Scale on Ecological Questions and Answers*, *in* LARGE-SCALE ECOLOGY AND CONSERVATION BIOLOGY 1, 3 (P.J. Edwards et al. eds., 1993). Coral reefs are very patchy environments. SALE, *supra* note 345, at 10.

349. Peter J. Mumby et al., *Spectrographic Imaging: a Bird's-eye View of the Health of Coral Reefs*, 413 NATURE 36 (2001).

350. J.B.C. Jackson, *Adaptation and Diversity of Reef Corals*, 41 BIOSCIENCE 475, 480-81 (1991). A recent study suggests that certain coral reefs are "hotspots" of endemic species. The ten richest centers of endemic species cover only 15.8% of the world's coral reefs but include about half of those species having restricted ranges. Callum M. Roberts et al. *Marine Biodiversity Hotspots and Conservation Priorities for Tropical Reefs*, 295 SCI. 1280 (2002).

351. *See generally* CARL SAFINA, SONG FOR THE BLUE OCEAN 303-434 (1998).

352. Terence P. Hughes, *Catastrophes, Phase Shifts, and a Large-Scale Degradation of a Caribbean Coral Reef*, 265 SCIENCE 1547 (1994); Nancy Knowlton, *Hard Decisions and Hard Science: Research Needs for Coral Reef Management*, *in* CORAL REEFS: CHALLENGES AND OPPORTUNITIES FOR SUSTAINABLE MANAGEMENT 183, 184-85 (Marea E. Hatziolos et al. eds., 1997) (maintaining that the healthy appearance of the Jamaican reefs in the 1970's masked the reef's susceptibility to disturbance).

sedimentation and waste disposal,[353] destructive reef-fishing techniques[354] and ocean-fishing techniques[355] have been blamed for some of the damage to coral reefs, many scientists fear that the underlying problem is the inability of coral reef systems to adapt to gradually warming water conditions caused by the increase of greenhouse gases in the atmosphere.[356]

One very noticeable change has been the bleaching of coral reefs in many parts of the world. The brilliant colors of coral reefs are supplied by algae that live in symbiotic relationship with the coral.[357] If the algae die off, the coral turns translucent in a process called bleaching.[358] The widespread bleaching of coral reefs that occurred during the 1997-98 El Niño episode[359] seemed to be far more extensive than the sporadic bleaching that occurred in the past.[360] The connection between bleaching and the increased water temperature during the El Niño was strengthened when the bleaching did not recur after the water temperature dropped in succeeding years.[361] There has been increasing concern that coral reefs will become a casualty of future climate change.[362]

Most scientists realize, however, that the lack of a good history of worldwide baseline data has made it difficult to determine if

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353. James W. Porter & Jennifer I. Tougas, *Reef Ecosystems: Threats to Their Biodiversity*, *in* 5 ENCYCLOPEDIA OF BIODIVERSITY 73, 82-83 (Simon A. Levin ed., 2001).

354. Hughes, *supra* note 352, at 1547-48. Collection of tropical fish for the aquarium market is a problem of increasing concern for the maintenance of coral reef ecological systems. U.S. EPA, OFFICE OF WATER, NATIONAL WATER QUALITY INVENTORY: 1998 REPORT TO CONGRESS 128-29 (1998).

355. Jeremy B.C. Jackson et al., *Historical Overfishing and the Recent Collapse of Coastal Ecosystems,* 293 SCIENCE 629, 631-33 (2001) (noting that large-scale trawling likely removed ocean fish that formerly kept algae and starfish under control).

356. Hoegh-Guldberg, *supra* note 346, at 843-44; Porter & Tougas, *supra* note 353, at 92-94. For a commentary on this thesis, see JAN SAPP, WHAT IS NATURAL?: CORAL REEF CRISIS 189-190 (1999). The United States National Oceanographic and Atmospheric Agency (NOAA) provides regular updates on coral bleaching conditions. *See* http://psbsgi1.nesdis.noaa.gov:8080/PSB/EPS/SST/climohot.html (last visited Mar. 5, 2002).

357. Hoegh-Guldberg, *supra* note 346, at 843-45.

358. JAN SAPP, WHAT IS NATURAL?: CORAL REEF CRISIS 190-91 (1999).

359. Clive Wilkinson et al., *Ecological and Socioeconomic Impacts of 1998 Coral Mortality in the Indian Ocean: An ENSO Impact and a Warning of Future Change?*, 28 AMBIO 188, 189, 192 (1999).

360. Hoegh-Guldberg, *supra* note 346, at 843-845.

361. Janice M. Lough, *Climate Variability and Change on the Great Barrier Reef, in* OCEANOGRAPHIC PROCESSES OF CORAL REEFS: PHYSICAL AND BIOLOGICAL LINKS IN THE GREAT BARRIER REEF 269, 275-77 (Eric Wolanski ed., 2001); William Skirving & John Guinotte, *The Sea Surface Temperature Story on the Great Barrier Reef during the Coral Bleaching Event of 1998, in* OCEANOGRAPHIC PROCESSES OF CORAL REEFS: PHYSICAL AND BIOLOGICAL LINKS IN THE GREAT BARRIER REEF 301, 305-08 (Eric Wolanski ed., 2001). For a readable summary of the history and current conditions on the Great Barrier Reef, see ROSALEEN LOVE, REEFSCAPE: REFLECTIONS ON THE GREAT BARRIER REEF (2001).

362. Porter & Tougas, *supra* note 345, at 92-94.

recent disturbances exceeded those in previous cycles.[363] We know that over long periods of time coral reefs have survived many changes in the level and temperature of the sea.[364] Our understanding of the ecology of coral reefs, and our ability to determine whether changes in their condition are normal or indicative of collapse, is being greatly advanced by the enhanced ability to compare different reefs around the world with each other and to explore their history over long time periods.[365] Worldwide, long-term monitoring is being established as part of an International Coral Reef Initiative[366] sponsored jointly by the Intergovernmental Oceanographic Commission, the United Nations Environment Program, and the World Conservation Union.[367] This is an example of the kind of international cooperation that is possible through the use of large-scale ecology.[368]

Some biologists are relatively optimistic about the reefs' future. Coral reefs may have greater recovery power than terrestrial ecosystems because the "aqueous medium is considered to buffer local variations and promote long-distance dispersal" thus promoting recolonization and genetic diversity.[369] Many of the coral reefs that are subject to frequent disturbance by tropical storms develop into highly heterogenous habitats in which many species are able to compete with each other because disturbance is frequent enough to prevent competitive exclusion.[370] Some biologists think

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363. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2001: IMPACT, ADAPTATION AND VULNERABILITY, A REPORT OF WORKING GROUP II OF THE Intergovernmental Panel on Climate Change, *at* www.usgcrp.gov/ipcc/wg2spm.pdf.

364. ROBERT J. WHITTAKER, ISLAND BIOGEOGRAPHY 15-17 (1998).

365. *Compare* David R. Bellwood & Terry P. Hughes, *Regional-Scale Assembly Rules and Biodiversity of Coral Reefs,* 292 SCIENCE 1532 (2001) ("Tropical reef fishes and corals exhibit highly predictable patterns of taxonomic composition across the Indian and Pacific Oceans.") *with* the more pessimistic view expressed a decade earlier in T. J. Done, *Phase Shifts in Coral Reef Communities and Their Ecological Significance,* 247 HYDROBIOLOGIA 121 (1992) ("[w]e do not have a good understanding of how population, community and ecosystem structure and function differ in degraded from un-degraded reefs."). *See also* Robert A. Kinzie III, *Sex, Symbiosis and Coral Reef Communities,* 39 AM. ZOOLOGIST 80 (1999) (suggesting that by studying reefs at larger scales we have a more realistic understanding of their natural processes).

366. Richard Kenchington, *Status of the International Coral Reef Initiative, in* CORAL REEFS: CHALLENGES AND OPPORTUNITIES FOR SUSTAINABLE MANAGEMENT 11, 11-14 (Marea E. Hatziolos et al. eds., 1998).

367. Clive Wilkinson & Bernard Salvat, *The Global Reef Monitoring Network: Reversing the Decline of the World's Reefs, in* CORAL REEFS: CHALLENGES AND OPPORTUNITIES FOR SUSTAINABLE MANAGEMENT 16, 17-18 (Marea E. Hatziolos et al. eds., 1998).

368. *See* discussion *supra* notes 23-33.

369. Marjorie L. Reaka-Kudla, *The Global Biodiversity of Coral Reefs: A Comparison with Rain Forests, in* BIODIVERSITY II: UNDERSTANDING AND PROTECTING OUR BIOLOGICAL RESOURCES 83, 101 (Marjorie L. Reaka-Kudla et al. eds., 1997).

370. Jason E. Tanner & Terence P. Hughes, *Species Coexistence, Keystone Species, and Succession: A Sensitivity Analysis,* 75 ECOLOGY 2204, 2217 (1994).

that it is these regularly disturbed reef systems that are most likely to attain a high degree of species richness and to adapt to environmental change.[371] Other scientists have suggested that corals may employ bleaching as a device to rid themselves of suboptimal algae and develop a new symbiosis with algae more adaptable to current environmental conditions.[372] On the other hand, none of these optimistic conjectures can yet be considered anything but a working hypothesis until a better database of large scale ecological data has been accumulated.

ii. Patterns in Time: The Example of Wilderness

The largest category of natural area that the United States has tried to protect is what we call "wilderness." By law, wilderness in the United States is defined as areas that retain their "primeval" character.[373] Does our system of wilderness protection accomplish ecological objectives when viewed from a long-range perspective?[374]

The legal protection of wilderness was not based on the ecological qualities of the chosen areas, but on the impact of these areas on humans. As John Muir put it, in the wilderness, "Nature's peace will flow into you as sunshine flows into trees."[375] The idea that nature has a beneficial impact on human emotions has, of course, a long history,[376] but our modern wilderness preservation laws grew out of an egalitarian New Deal-era desire to improve human character by making it possible for everyone to escape what

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371. RICKLEFS, *supra* note 58, at 565-66 (citing the intermediate disturbance hypothesis, discussed *infra* notes 397-402, as the probable cause of species richness in coral reefs subject to disturbance). Other coral reef ecological systems, which have evolved during stable conditions in areas where storms are infrequent, may have low resilience because there have been few disturbances, and such systems may be unable to restore their original conditions after eutrophication, overfishing, or other significant human-caused disturbances. AnnMari Jansson & Bengt-Owe Jansson, *Ecosystem Properties as a Basis for Sustainability*, *in* INVESTING IN NATURAL CAPITAL: THE ECOLOGICAL ECONOMICS APPROACH TO SUSTAINABILITY 74, 87 (AnnMari Jansson et al. eds., 1994). This hypothesis is conjectural. *See* Robert H. Fraser & David J. Currie, *The Species Richness-energy Hypothesis in a System Where Historical Factors Are Thought to Prevail: Coral Reefs*, 148 AM. NATURALIST 138, 148 (1996) (pointing out that little evidence supports the theory that disturbance promotes species richness in reefs).

372. Andrew C. Baker, *Reef Corals Bleach to Survive Change*, 411 NATURE 765-66 (2001). This theory is conjectural. Hoegh-Guldberg *supra* note 346, at 856. Some biologists suggest that a reduction in the intervals between bleaching episodes could cause a conversion to short-lived coral species. Terence J. Done, *Coral Community Adaptability to Environmental Change at the Scales of Regions, Reefs and Reef Zones*, 39 AM. ZOOLOGIST 66, 73-75 (1999).

373. *See* discussion *supra* notes 379-81.

374. *See generally* NOSS & COOPERRIDER, *supra* note 194, at 172-74.

375. JOHN MUIR, OUR NATIONAL PARKS 42 (Sierra Club Books ed., 1991).

376. *See, e.g.*, RAYMOND WILLIAMS, THE COUNTRY AND THE CITY (1973). Edward O. Wilson suggests that the attraction for nature may be genetically entrained in humans. *See generally* EDWARD O. WILSON, BIOPHILIA (1984).

Bob Marshall, the founder of the Wilderness Society, called the "serious retrogression, physical, moral and mental" that results from living in cities.[377] The idea that humans can experience a spiritual transformation through contact with the wilderness remains a powerful motivation for the protection of large areas unoccupied by humans.[378]

Formal recognition of the wilderness concept reached its peak in the 1960s with the adoption of the Wilderness Act.[379] The Act proposes that Congress shall set aside large tracts of "land retaining its primeval character and influence . . . ."[380] Pursuant to the statute, an area twice the size of Nebraska has been set aside in the western United States to be available only to those who hike and camp.[381] Organizations such as the Sierra Club and the Wilderness Society reflect the views of millions of people who defend "wildness" as a value in its own right, wholly apart from any ecological issues.

Is there an ecological basis for the protection of wilderness? Many designated wilderness areas were undoubtedly available for such designation because humans had passed them by due to their low productivity.[382] High altitudes, low rainfall, or cold temperatures are characteristic of many wilderness areas, and these often signify low ecological productivity as well, so we cannot tie wilderness protection to maintenance of productivity.[383] A recent analysis of endangered species in five states concluded that

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377. ROBERT GOTTLIEB, FORCING THE SPRING: THE TRANSFORMATION OF THE AMERICAN ENVIRONMENTAL MOVEMENT 16 (1993). For a contemporary example of the egalitarian influence on wilderness protection, see Gary Snyder, *The Etiquette of Freedom, in* THE WILDERNESS CONDITION: ESSAYS ON ENVIRONMENT AND CIVILIZATION 21, 38 (Max Oelschlaeger ed., 1992) ("We can accept each other all as barefoot equals sleeping on the same ground.").

378. WILSON, *supra* note 297, at 145-48. J. Ronald Engel, *Liberal Democracy and the Fate of the Earth, in* SPIRIT AND NATURE: WHY THE ENVIRONMENT IS A RELIGIOUS ISSUE 59, 68 (Steven C. Rockefeller & John C. Elder eds., 1992).

379. The 1964 Wilderness Act is codified at 16 U.S.C. §§ 1131-36 (1964). For the history of the Act's adoption, see Robert L. Glicksman & George Cameron Coggins, *Wilderness in Context*, 76 DENV. U. L. REV. 383, 384-89 (1999). *See also* WILLIAM K. WYANT, WESTWARD IN EDEN 281 (1982).

380. 16 U.S.C. § 1131(c). For a discussion of the operation of the statute in practice, see Robert B. Keiter, *Taking Account of the Ecosystem on the Public Domain: Law and Ecology in the Greater Yellowstone Region*, 60 U. COLO. L. REV. 923, 951-56 (1989).

381. ERIC T. FREYFOGLE, JUSTICE AND THE EARTH: IMAGES FOR OUR PLANETARY SURVIVAL 97 (1993).

382. Jonathan S. Adams et al., *Biodiversity: Our Precious Heritage, in* PRECIOUS HERITAGE: THE STATUS OF BIODIVERSITY IN THE UNITED STATES 3, 17 (Bruce A. Stein et al. eds., 2000).

383. A study of all nature reserves in the United States, including wilderness areas, found that many were characterized by high elevation and soil of low productivity. J. Michael Scott et al., *Nature Reserves: Do They Capture the Full Range of America's Biological Diversity?*, 11 ECOLOGICAL APPLICATIONS 999, 1003 (2001).

most of the species at risk are those that occupy human-dominated areas, not wilderness.[384] We need to recognize that wilderness areas were not selected on the basis of any ecological criteria.[385]

Few wilderness areas are immune from the changes arising from the operation of patch dynamics.[386] Even with minimal human intrusion, landscape ecological processes are continually causing changes to which organisms respond; for example, warming temperatures have gradually changed habitat conditions in many cold-climate wilderness areas.[387] Also, human activities outside the wilderness areas have removed some of the largest predators, which has had cascading effects down food chains.[388] The reintroduction of large predators into some wilderness areas may help restore ecological balance by reducing overpopulation of deer and other herbivores.[389]

Many conservation biologists would like to redefine wilderness areas originally set aside for other reasons as biodiversity reservoirs that could be expanded.[390] But few of the "hotspots" of rare species or habitats are found in American wilderness areas.[391]

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384. Andrew P. Dobson et al., *Synoptic Tinkering: Integrating Strategies for Large Scale Conservation*, 11 ECOLOGICAL APPLICATIONS 1019, 1019 (2001).

385. Reed Noss, Reconciling Conservation of Species and Ecosystems (A paper delivered at the Conference on Integration across Ecological Scales, Texas A&M University, Feb. 25, 2000.)

386. *See* David M. Graber, *Resolute Biocentrism: The Dilemma of Wilderness in National Parks, in* REINVENTING NATURE: RESPONSES TO POSTMODERN DECONSTRUCTION 123, 125-131 (Michael E. Soulé & Gary Lease eds., 1995); Lech Ryszkowski, *The Coming Change in the Environmental Protection Paradigm, in* IMPLEMENTING ECOLOGICAL INTEGRITY: RESTORING REGIONAL AND GLOBAL ENVIRONMENTAL AND HUMAN HEALTH 37, 52 (Phillip Crabbé et al. eds., 2000) (noting that all reserves are changing as a result of external impacts).

387. *See* discussion *infra* notes 471-74.

388. Aldo Leopold pioneered in the recognition of predation as an important component of what he called "land health." *See, e.g.*, Aldo Leopold, *The Land-Health Concept and Conservation, in* FOR THE HEALTH OF THE LAND 218, 225 (J. Baird Callicott & Eric T. Freyfogle eds., 1999).

389. The legal, scientific, and social implications of reintroduction are quite complex and beyond the scope of this article. *See, e.g.* Wyoming Farm Bureau Fed'n v. Babbitt, 199 F.3d 1224 (10th Cir. 2000) (upholding reintroduction of wolves in Yellowstone). For discussion of the case, see A. Dan Tarlock, *The Future of Environmental "Rule of Law" Litigation*, 17 PACE ENVTL. L. REV. 237, 268-69 (2000) (analyzing Yellowstone wolf reintroduction litigation); Federico Cheever, *From Population Segregation to Species Zoning: The Evolution of Reintroduction Law under Section 10(J) of the Endangered Species Act*, 1 WYO. L. REV. 287, 362-63 (2001).

390. J. Baird Callicott et al., *Current Normative Concepts in Conservation*, 13 CONSERVATION BIOLOGY 22, 32 (1999). A study of the roadless areas in the national forests concluded that the creation of conservation reserves in these areas would substantially increase the amount of reserve area at lower elevations than most wilderness areas. Robert l. DeVelice & Jon R. Martin, *Assessing the Extent to which Roadless Areas Complement the Conservation of Biological Diversity*, 11 ECOLOGICAL APPLICATIONS 1008 (2001).

391. The places on the planet judged by Conservation International to be key areas requiring protection are beautifully photographed and described in RUSSELL W.

From an ecological standpoint, perhaps the most important reason for the preservation of wilderness is the recognition that our scientific understanding of the values of natural areas is still far from perfect.[392] We know that environmental conditions will be changing, though the predictability of such changes remains elusive.[393] The continued existence of large tracts of natural landscape may serve as laboratories in which the ecologists of the future may perfect their craft.[394]

But there is no reason to try to tie wildness and ecology too closely, because we should not be embarrassed to recognize that we have reasons to protect landscapes that are not founded on ecological science.[395] The powerful desire to protect the remaining wilderness areas, as exemplified in the debates over the Arctic National Wildlife Refuge, reflects the importance of the emotional attachment to what are called "existence" values – the desire to know that wild places exist even if one will never utilize them.[396] It is not my intent to disparage these values — only to point out that it is incorrect to think of them as ecological values in any scientific sense.

MITTERMEIER, HOTSPOTS: EARTH'S BIOLOGICALLY RICHEST AND MOST ENDANGERED TERRESTRIAL ECOREGIONS (First English ed., 1999). Similar programs for identifying hotspots of biodiversity have been undertaken by the World Wildlife Fund. DAVID M. OLSON & ERIC DINERSTEIN, THE GLOBAL 200: A REPRESENTATION APPROACH TO CONSERVING THE EARTH'S DISTINCTIVE ECOREGIONS (1998). The Nature Conservancy has long been acquiring land in such areas. Adams, *supra* note 382, at 10-11. It recently acquired an entire Pacific atoll for conservation. Suzanne Case, *Palmyra Atoll: October 31 to November 4, 2000*, 7 HASTINGS W.-NW. J. ENVTL. L. & POL'Y 291 (2001). *See also* Kai N. Lee, *Searching for Sustainability in a New Century*, 27 ECOLOGY L.Q. 913, 921-922 (2001).

392. FREYFOGLE, *supra* note 381, at 99-100.

393. DANIEL B. BOTKIN, NO MAN'S GARDEN: THOREAU AND A NEW VISION FOR CIVILIZATION AND NATURE 239 (2001).

394. *See* Bill Willers, *Toward a Science of Letting Things Be*, *in* UNMANAGED LANDSCAPES: VOICES FOR UNTAMED NATURE 57 (Bill Willers ed.,1999) ("[I]f left alone so that its processes can continue in an unmanaged way, a vast ecosystem . . . becomes a teacher."). Or as Justice Douglas put it, man will recognize the elements of the wilderness as "links in a chain of which he too is a part" and "perhaps solve some of its mysteries." WILLIAM O. DOUGLAS, MY WILDERNESS: EAST TO KATAHDIN 290 (1961).

395. For an international perspective on the idea of wilderness, see NATURE'S LAST STRONGHOLDS 10-12 (Robert Burton ed., 1991).

396. *See* DAVID W. PEARCE, ECONOMIC VALUES AND THE NATURAL WORLD 21-22 (1993); Howard F. Chang, *An Economic Analysis of Trade Measures to Protect the Global Environment*, 83 GEO. L.J. 2131, 2169-70 (1995) (advocating expansive use of such values); Jan G. Laitos & Thomas A. Carr, *The Transformation on Public Lands*, 26 ECOLOGY L.Q. 140, 227-41 (1999) (suggesting that public support for existence values will dominate use of public lands in the future). For a critique of the methodology by which analysts try to quantify existence values, see Donald J. Boudreaux et al., *Talk is Cheap: The Existence Value Fallacy*, 29 ENVTL. L. 765 (1999).

3. The Rhythm of Disturbance is Crucial

The previous discussion suggests that disturbance itself is not necessarily a danger to ecological systems. In fact, the benefits of disturbance for the maintenance of ecological processes are beginning to be more clearly understood. But ecologists emphasize that disturbance is valuable only as long as the frequency or extent of disturbance does not exceed "normal" limits. To understand what level of disturbance is normal, ecologists need to study disturbance over extended scales of space and time.

i. Disturbance Can Enhance Species Richness

One result of the study of disturbance has been the realization that a certain amount of disturbance seems to be necessary to promote the form of biodiversity known as species richness.[397] Although the relationship between disturbance and diversity is complex, both too much and too little disturbance seem to reduce diversity of species.[398] This phenomenon is familiarly known to ecologists as the "intermediate-disturbance" hypothesis.[399]

Why does diversity of species peak at intermediate disturbance frequencies? If disturbance is too frequent, few species have time to move in and settle. But if disturbance is rare, competition has time to reduce diversity through competitive exclusion. At intermediate levels, more species accumulate before the disturbance, but disturbance happens often enough to slow the process of competitive exclusion.[400] Therefore, although many

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397. Species richness is the diversity of species in a community. It is measured by comparing the number of species in a community to the total number of organisms in the community. A DICTIONARY OF ECOLOGY, *supra* note 147, *at* 380.

398. *See, e.g.*, Warren D. Allmon et al., *An Intermediate Disturbance Hypothesis of Maximal Speciation, in* BIODIVERSITY DYNAMICS: TURNOVER OF POPULATIONS, TAXA AND COMMUNITIES 349 (Michael L. McKinney & James A. Drake eds., 1998); Peter S. White & Jonathan Harrod, *Disturbance and Diversity in a Landscape Context, in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 128, 140-52 (John A. Bissonette ed., 1997).

399. Frank Davis & Max Moritz, *Mechanisms of Disturbance, in* 2 ENCYCLOPEDIA OF BIODIVERSITY 153, 155 (Simon A. Levin ed., 2001); NANAKO SHIGESADA & KOHKICHI KAWASAKI, BIOLOGICAL INVASIONS: THEORY AND PRACTICE 128 (1997). For a history of the theory's origins, see Robert M. May, *The Effects of Spatial Scale on Ecological Questions and Answers, in* LARGE-SCALE ECOLOGY AND CONSERVATION BIOLOGY 1, 4 (P.J. Edwards et al. eds., 1994).

400. *See* ROSENZWEIG, *supra* note 261, at 341-42. *See also* HUSTON, *supra* note 285, at 35 (noting that many studies have found the "highest species diversity occurs at intermediate frequencies of disturbance, with low diversity at both very high and very low frequencies."); Peter Chesson & Nancy Huntly, *The Roles of Harsh and Fluctuating Conditions in the Dynamics of Ecological Communities*, 150 AM. NATURALIST 521, 544 (1997) (modeling suggests that disturbances allow species with differing responses to disturbance to coexist when they might otherwise be excluded by competition). *But see* MUTSONORI TOKESHI, SPECIES COEXISTENCE: ECOLOGICAL AND EVOLUTIONARY PERSPECTIVES 280-281(1999)

species have developed resilient adaptation to certain levels of disturbance,[401] changes in the historical pattern of disturbances would be likely to have an impact on the diversity of species in the area.[402]

ii. Disturbance Can Enhance Resilience

The diversity that results from disturbances may be an advantage to an ecological system because it gives it the "resilience" that will enable it to withstand continuing environmental disruption.[403] The term resilience is increasingly being used to describe the extent to which a natural area can reorganize itself after disturbance.[404] In the language of nonequilibrium ecology, resilience refers to the ability of an ecological system to withstand disturbance without flipping to another stability domain.[405]

Estuaries are an example of a kind of ecological system that often builds up a good deal of resilience. They are often flooded with fresh water by high rains and by salt water from ocean storms, and they may periodically undergo drought.[406] Some estuaries have been subject to a high rate of such disturbance,[407] and ecologists now suspect that it is these disturbances that prevent a small number of species from dominating the estuarine habitat. Estuaries may not build up resilience unless the system has dealt with enough disturbance to preclude competitive exclusion.[408]

Holling suggests that the resilience of ecological systems is determined by the processes by which the systems self-organize

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(maintaining that the intermediate disturbance hypothesis is "disappointingly superficial" because one can always assume a higher or lower rate of disturbance).

401. *See, e.g.* Jones et al., *supra* note 63, at 2628 (noting that cerulean warblers adapted to new territory sizes and nest locations after a severe ice storm in Quebec).

402. Monica G. Turner et al., *Ecological Dynamics at Broad Scales: Ecosystems and Landscapes, in* BIOSCIENCE S-29, S-31 (SCIENCE AND BIODIVERSITY POLICY 1995).

403. *See* J.B. Ruhl, *Thinking of Environmental Law as a Complex Adaptive System: How to Clean Up the Environment by Making a Mess of Environmental Law*, 34 HOUS. L. REV. 933, 951-52 (1997).

404. Holling, *supra* note 139, at 481. *See also* RICK POTTS, HUMANITY'S DESCENT: THE CONSEQUENCES OF ECOLOGICAL INSTABILITY 225 (1996).

405. Lance H. Gunderson, *Ecological Resilience - In Theory and Application*, 31 ANN. REV. OF ECOLOGY & SYSTEMATICS 425, 426 (2000). In equilibrium ecology, resilience is related to the ability of an ecological system to return to equilibrium after disturbance. STUART L. PIMM, THE BALANCE OF NATURE? ECOLOGICAL ISSUES IN THE CONSERVATION OF SPECIES AND COMMUNITIES 18 (1991).

406. *See* Giulio A. De Leo & Simon A. Levin, *The Multifaceted Aspects of Ecosystem Integrity*, 1 CONSERVATION ECOLOGY 1997, *available at* www.consecol.org/vol1/iss1/art3.

407. *See, e.g.*, Hans W. Paerl et al., *Ecosystem Impacts of Three Sequential Hurricanes (Dennis, Floyd, and Irene) on the United States' Largest Lagoonal Estuary, Pimlico Sound, NC*, 98 PROC. NAT'L ACAD. SCI. USA 5655 (2001).

408. THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS, *supra* note 331, at 379.

after disturbance. "Resilience and recovery are determined by the release and reorganization sequence, whereas stability and productivity are determined by the exploitation and conservation sequence."[409] The ability to reorganize, in turn, will be affected by the diversity of species remaining after the disturbance. Species richness is important during periods of environmental fluctuation, when

> . . . the ability to survive rather than efficient function is favored . . . . The presence of a diversity of species and functional types will be of paramount importance for the continuity of ecosystems when faced with environmental shifts . . . . Ecosystems are able to recover because they are formed of many species, each of which has a unique set of characteristics.[410]

This species richness "provides the system with the resilience to respond to unpredictable surprises."[411]

This phenomenon is sometimes referred to as the "insurance effect" of diversity.[412] Ecological systems can be viewed as "organic aggregates maintaining their integrity and continuity in time in a variable and fluctuating environment. From this point of view, the persistence of the entire system, i.e., resilience, is the variable of interest, and not the constancy of its functions."[413] The ability of humans to function so effectively may be a result of the resilience we built up because of our continuing need to cope with environmental change.[414]

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409. Holling, *supra* note 139, at 481.

410. O.T. Solbrig, *Plant Traits and Adaptive Strategies: Their Role in Ecosystem Function*, *in* BIODIVERSITY AND ECOSYSTEM FUNCTION 97, 110-11. (Ernst-Detlef Schulze & Harold A. Mooney eds., 1994)

411. *Id.* at 111.

412. Michael Loreau, *Biodiversity and Ecosystem Functioning: Recent Theoretical Advances*, 91 OIKOS 3, 13 (2000). *See also* Charles Perrings, *Biodiversity Conservation as Insurance*, *in* THE ECONOMICS AND ECOLOGY OF BIODIVERSITY DECLINE: THE FORCES DRIVING GLOBAL CHANGE 69 (Timothy M. Swanson ed., 1995).

413. Solbrig, *supra* note 410, at 108.

414. The Smithsonian Institution's Rick Potts has elaborated on the theory of disturbance-generated resilience to suggest that the dominance of *Homo sapiens* is a result of our ability to react to nature's perturbations:

> Our lineage arose as large, periodic fluctuations governed the conditions of survival. The effects were felt by the hominids and experienced by the biotic world at large. The distinguishing qualities of human culture emerged later, attached to extreme, repetitive shifts in climate and biota. The power to alter our surroundings grew stronger as a way of

Resource managers who use too short a time frame often fail to acknowledge that such disturbances as fire, flood, and disease are part of natural ecological cycles.[415] Authors in the relatively new field of "ecological economics" are devoted to the study of "coevolutionary development of human beings and the natural world"[416] and have addressed the need to include information about both economic and ecological cycles in economic decision-making processes.[417] Allen and Hoekstra point out that if viewed at an appropriate time scale "almost all processes that at first appear to be a linear progression will emerge as cyclical.... Individual fires are directional and have a before and after; nevertheless, fires return in a fire cycle."[418]

Resource managers increasingly recognize that it would be short-sighted to treat each disturbance as a one-time event and focus on it exclusively.[419] Indiscriminate use of techniques such as insecticides, fire suppression and fish hatcheries may slowly reduce heterogeneity in favor of uniformity, which then enlarges the area at risk. For example, if there are fewer breaks in the forest, disease

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> moderating erratic environmental change. The results were intimate and consistent with nature's own periodic facelift. This outlook on our evolution differs sharply from the tenets about nature and humanness lodged in Western thought.

RICK POTTS, HUMANITY'S DESCENT: THE CONSEQUENCES OF ECOLOGICAL INSTABILITY 44 (1996). *See also* STEVE JONES, THE LANGUAGE OF THE GENES 199-206 (1993) (noting that humans went through dramatic environmental change). Mahdav Gadgil argues that this long history of environmental change has programmed people to be attracted to conserving artifacts along with nature. Mahdav Gadgil, *Of Life and Artifacts, in* THE BIOPHILIA HYPOTHESIS 365, 366-67 (Stephen R. Kellert & Edward O. Wilson eds., 1993).

415. *See* De Leo & Levin, *supra* note 406, (noting that attempts by resource managers to attain stability have led to a loss of resiliency that has produced worse crises than in unmanaged ecosystems).

416. THOMAS PRUGH ET AL., NATURAL CAPITAL AND HUMAN ECONOMIC SURVIVAL 21 (1995).

417. Kenneth Arrow et al., *Economic Growth, Carrying Capacity, and the Environment*, 268 SCI. 520 (1995).

418. T.F.H. ALLEN & THOMAS W. HOEKSTRA, TOWARD A UNIFIED ECOLOGY 20 (1992).

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> Conventional resource management is predisposed to block out disturbance, which may be "efficient" in a limited sense in the short term. But since disturbance is endogenous to the cyclic processes of ecosystem renewal, conventional resource management tends to increase the potential for larger-scale disturbances and even less predictable and less manageable feedbacks from the environment. These feedbacks, or surprises, can have devastating effects on ecosystems and on societies that depend on the resources and services that ecosystems generate. As resilience or the buffering capacity of the system gradually declines, flexibility is lost, and the linked social-ecological system becomes more vulnerable to surprise and crisis.

Carl Folke et al., *Ecological Practices and Social Mechanisms for Building Resilience and Sustainability, in* LINKING SOCIAL AND ECOLOGICAL SYSTEMS: MANAGEMENT PRACTICES AND SOCIAL MECHANISMS FOR BUILDING RESILIENCE 414, 415-16 (Fikret Berkes & Carl Folke eds., 1998) (citations omitted).

may spread more easily. In grasslands, exotics that outcompete drought-resistant grasses may spread more widely in homogeneous environments. In fisheries, wild species may be driven out by increased non-native hatchery introduced fish, leaving the industry dependent on hatcheries whose productivity declines with time.[420]

Examination of disturbance regimes over long time scales has led to attempts to discern patterns of disturbance that would assist the forecast of future disturbance. One result of this research is the exploration of the idea that disturbance regimes may generally follow a pattern of long periods of stability interrupted by short bursts of change.[421] Some biologists have commented on the fact that the new emphasis on dramatic ecological change is analogous to current evolutionary biology theorists rejecting the traditional notion that evolution is necessarily a continuous process of gradual change.[422] Using the seminal paper of Gould and Eldredge as a basis, many evolutionary biologists believe that evolution is characterized by "punctuated equilibrium," in which long periods of relatively minor changes are periodically interrupted by periods in which change takes place rapidly in response to some form of change in environmental conditions.[423] Although gradual change also occurs, it often seems to be simply "a sort of oscillation within a spectrum of possible states."[424] Ecologists recognize the need for

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420. C.S. Holling, *New Science and New Investments for a Sustainable Biosphere*, *in* INVESTING IN NATURAL CAPITAL: THE ECOLOGICAL ECONOMICS APPROACH TO SUSTAINABILITY 57, 67-68 (AnnMari Jansson et al. eds., 1994). Although catastrophic disturbance may be the most important variable affecting resource management, it is also the hardest one to predict successfully. Craig L. Shafer, *Terrestrial Nature Reserve Design at the Urban/Rural Interface*, *in* CONSERVATION IN HIGHLY FRAGMENTED LANDSCAPES 345, 351 (Mark W. Schwartz ed., 1997).

421. Punctuated equilibrium results in increased speciation because the emptying of niches after severe disturbance causes rapidly increased birth rates, and speciation correlates with birth rate; i.e., a certain, constant, small percentage of births will result in new species. HUBBELL, *supra* note 39, at 236-37.

422. PER BAK, HOW NATURE WORKS: THE SCIENCE OF SELF-ORGANIZED CRITICALITY 117-118, 141-142, 156-159 (1996). *See* PETER J. BOWLER, EVOLUTION: THE HISTORY OF AN IDEA 336-341 (rev. ed. 1989).

423. Extended periods of little change in ecological systems are sometimes referred to as "coordinated stasis," and there is considerable debate over whether this results simply from the fitness adjustment of the individual species or from organization at the community level. Richard B. Aronson & Roy E. Plotnick, *Scale-Independent Interpretations of Macroevolutionary Dynamics*, *in* BIODIVERSITY DYNAMICS: TURNOVER OF POPULATIONS, TAXA AND COMMUNITIES 430 (Michael L. McKinney & James A. Drake eds., 1998). For an analysis of the spread of the concept of punctuated equilibrium to other fields, see Connie J.G. Gersick, *Revolutionary Change Theories: A Multilevel Exploration of the Punctuated Equilibrium Paradigm*, 16 ACAD. MGMT. REV. 10 (1991). The original paper is Niles Eldredge & Stephen Jay Gould, *Punctuated Equilibria: An Alternative to Phyletic Gradualism*, *in* MODELS IN PALEOBIOLOGY 82 (Thomas J.M. Schopf ed., 1972). *See also* Stephen Jay Gould & Niles Eldredge, *Punctuated Equilibrium Comes of Age*, 366 NATURE 223 (1993).

424. NILES ELDREDGE, TIME FRAMES: THE EVOLUTION OF PUNCTUATED EQUILIBRIA 145

more research into the impacts of cyclical landscape phenomena, such as the oscillation of warm and cold waters in the Pacific Ocean.[425] Similarly, today's ecologists are beginning to recognize that ecological changes "tend not to proceed in smooth and even steps but rather in fits and starts,"[426] and that the analysis of those fits and starts may prove most productive.[427] Ecologists' growing ability to analyze ecological information over long time frames allows them to use the study of disturbance with increasingly important effect in the protection of biodiversity.[428]

Complexity theorists say that some current studies of ecological disturbance illustrate more general theories of complexity.[429] Complexity researchers seek to find common principles that govern the evolution of all complex adaptive systems.[430] Whether or not scientists will discover overall patterns of complexity that can be used to forecast and manage disturbance, ecologists at least know that even if some disturbance may be desirable, it does not follow that all disturbance is desirable. Finding the boundary between "good" and "bad" disturbance is one of the most challenging issues of today's ecology.[431]

(1985). Holling argues that ecological systems don't have a single equilibrium; they have multiple equilibria that define functionally different states, and non-linear movement between these states is a natural part of maintaining structure and diversity. Bryan G. Norton, *A Scalar Approach to Ecological Constraints*, *in* ENGINEERING WITHIN ECOLOGICAL CONSTRAINTS 45, 50-51 (Peter C. Schulze ed., 1996) (suggesting that "Holling's ideas . . . may usher in a new era in thinking about environmental management, an era that is more concerned with processes, functions, and thresholds, and less concerned with system behavior near equilibrium."). *See also* JAMES H. BROWN, MACROECOLOGY 192-93 (1995) (discussing the idea that periods of apparent stasis may reflect species shifting their geographic environment in response to gradual changes in climate or other environmental factors).

425. John N. Thompson et al., *Frontiers of Ecology*, 51 BIOSCIENCE 15 (2001).

426. FIKRET BERKES, SACRED ECOLOGY: TRADITIONAL ECOLOGICAL KNOWLEDGE AND RESOURCE MANAGEMENT 160 (1999). *See also* CARL WALTERS, ADAPTIVE MANAGEMENT OF RENEWABLE RESOURCES 32-34 (1986) (discussing rhythms of crises and opportunities).

427. For example, a recent study ambitiously attempts to recreate the paths of all of the hurricanes that have impacted New England since 1620 and to trace the history of their ecological effects. Emery R. Boose et al., *Landscape and Regional Impacts of Hurricanes in New England*, 71 ECOLOGICAL MONOGRAPHS 27 (2001).

428. Frank Davis & Max Moritz, *Mechanisms of Disturbance*, *in* 2 ENCYCLOPEDIA OF BIODIVERSITY 153, 155 (Simon A. Levin ed., 2001).

429. *See, e.g.*, J.B. Ruhl, *supra* note 403. *See also* LEVIN, *supra* note 91.

430. For a useful introduction to complexity theory, see ROGER LEWIN, COMPLEXITY: LIFE AT THE EDGE OF CHAOS (1992). For a quick summary, see Walter Fontana & Susan Ballati, *Complexity: Why the Sudden Fuss?*, 4 COMPLEXITY #3, 14 (1999).

431. For an interesting philosophical discussion of the "randomness" of environmental change and its impact on human behavior, see Mark A. Michael, *How to Interfere with Nature*, 23 ENVTL. ETHICS 135 (2001).

D. *Metastability May Exist Without Equilibrium*

With the growing agreement of ecologists that a permanent state of equilibrium is not the normal state of nature, some observers have lamented the prospect of a natural world without meaningful Platonic ideals.[432] But others, including many ecologists, see the prospect of relatively stable states of constant motion.[433] Scientists coined the term "metastability" to describe a condition in which irregular disturbances at one scale enable an ecological system to find something akin to stability at a higher level.[434]

1. Can Regular Patterns of Change Create Long-Term Stability?

Ecological metastability, ecologist Jianguo Wu suggests, it is "possibly the closest technical equivalent to 'balance of nature.'"[435] It is a combination of instabilities that create stability.[436] "As long as the landscape system oscillates around a central position, it is in a metastable equilibrium."[437]

The observation of nature at large scales of space and time typically results in the recognition of patterns undetected at closer range.[438] Over short periods of time in small areas, species diversity may appear to vary greatly, while at continental and evolutionary scales, species diversity may appear to be in equilibrium.[439] Similarly, stocks of biomass and nutrients vary

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432. *See, e.g.*, Godlovitch, *supra* note 339.

433. *See, e.g.*, Peggy L. Fiedler et al., *The Paradigm Shift in Ecology and its Implications for Conservation, in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 83, 85-86 (Steward T.A. Pickett et al. eds, 1997).

434. Wu & Loucks, *supra* note 129, at 439.

435. *Id.* at 459. *See also* Peter Chesson, *Metapopulations, in* 4 ENCYCLOPEDIA OF BIODIVERSITY 161, 175 (Simon A. Levin ed., 2001) (noting that equilibrium occurs at large spatial and temporal scales); Ahl & Allen, *supra* note 124, at 169-71 (noting that ecological systems can evolve to a higher level of organization when response to disturbance has "become incorporated into the system"). The hierarchy theory of ecology rests on an assumption that metastable subsystems exist. "The guild, as a functional unit, is more constant, stable and enduring than any of the individual species that comprise it." R.V. O'NEILL, ET AL., A HIERARCHICAL CONCEPT OF ECOSYSTEMS 121 (1986). Other ecologists have used the term "quasi-equilibrium landscape" to represent a similar concept. H.H. Shugart, *Equilibrium Versus Non-equilibrium Landscapes, in* ISSUES IN LANDSCAPE ECOLOGY 18, 19 (John A. Wiens & Michael R. Moss eds., 1999).

436. "Metastability . . . is not an intermediate condition between instability and stability. Rather, it is a combination of the two properties." FORMAN & GODRON, *supra* note 236, at 436. *See, e.g.*, Alan A. Berryman et al., *Metastability of Forest Systems Infested by Bark Beetles*, 26 RESEARCHES ON POPULATION ECOLOGY 13 (1984).

437. FORMAN & GODRON, *supra* note 236, at 431.

438. BRIAN A. MAURER, UNTANGLING ECOLOGICAL COMPLEXITY: THE MACROSCOPIC PERSPECTIVE 140-41 (1999).

439. Michael L. McKinney, *Biodiversity Dynamics: Niche Preemption and Saturation in Diversity Equilibria, in* BIODIVERSITY DYNAMICS: TURNOVER OF POPULATIONS, TAXA, AND

greatly on small scales because vegetation changes frequently, but may appear roughly constant when observed at large scales.[440]

Is the hope to find metastability in the combination of multiple instabilities just wishful thinking?[441] Is there reason to hope that a metastable environment will generate the same aesthetic appeal and emotional excitement that humans have obtained from thinking of the natural world as stable? Is ecologist Daniel Botkin correct that "the beauty in the dynamics of nature can replace the beauty of the idea of stasis?"[442]

Metastability would be possible only if the changes we make to the environment are not unidirectional.[443] Environmental historian Donald Worster emphasizes the need to distinguish between cyclical change and linear change.[444] Moderate swings back and forth in climate, land cover, species dominance, and other ecological conditions could presumably be tolerated in a metastable world,[445] but if changes are only in one direction we are going to need to operate in a world of continuous, unpredictable change.[446]

COMMUNITIES 1, 3 (Michael L. McKinney & James A. Drake eds., 1998); Mooney et al., *supra* note 213, at 313 (noting that shifting patches of landscape may reach a steady state).

440. Peter M. Vitousek, *Community Turnover and Ecosystem Nutrient Dynamics, in* THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS 325, 333 (Steward T.A. Pickett & P.S. White eds., 1985).

441. Complexity theorists are also searching for evidence of metastability in ecological systems. *See* KUNIHIKO KANEKO & ICHIRO TSUDA, COMPLEX SYSTEMS: CHAOS AND BEYOND 179-190 (2000) (arguing that "homeochaos" protects diversity against disturbance by avoiding violent change in population dynamics).

442. DANIEL B. BOTKIN, NO MAN'S GARDEN: THOREAU AND A NEW VISION FOR CIVILIZATION AND NATURE 239 (2001).

443. V. Ingegnoli, *Human Influences in Landscape Change: Thresholds of Metastability, in* TERRESTRIAL AND AQUATIC ECOSYSTEMS: PERTURBATION AND RECOVERY 303 (Oscar Ravera ed., 1991) (suggesting outline of model for threshold of metastability). For example, it has been estimated that the steady, gradual urbanization of South Florida has caused climate changes resulting in a significant decrease in summer rainfall. R.A. Pielke, Sr. et al., *The Influence of Anthropogenic Landscape Changes on Weather in South Florida*, 127 MONTHLY WEATHER REV. 1663 (1999).

444. Donald Worster, *Nature and the Disorder of History, in* REINVENTING NATURE?: RESPONSES TO POSTMODERN DECONSTRUCTION 65, 81-82 (Michael E. Soulé & Gary Lease eds., 1995).

445. "The biosphere is always changing in response to cycles." WILLIAM H. SCHLESINGER, BIOGEOCHEMISTRY: AN ANALYSIS OF GLOBAL CHANGE 8 (2d ed. 1997). Holling refers to the phenomenon of "[a]brupt shifts among a multiplicity of very different stable domains" in such areas as lakes, marine fisheries, wetlands, forests and rangelands. C.S. HOLLING ET AL., FINAL REPORT OF THE PROJECT: RESILIENCE OF ECOSYSTEMS, ECONOMIC SYSTEMS AND INSTITUTIONS, April 30, 2000, at p. 4. *See also* Johan van de Koppel et al., *Do Alternate Stable States Occur in Natural Ecosystems? Evidence from a Tidal Flat*, 82 ECOLOGY 3449 (2001) (functional relationships among erosion, silt content, and diatom growth lead to alternate stable states in tidal flat ecological systems).

446. See *infra* text accompanying notes 718-754.

2. Today's Rate of Environmental Change is Unprecedented

Many scientists fear that the earth's ecological systems are now experiencing change at a rate that previously occurred only during global catastrophes,[447] such as the one that characterized the Cretaceous/Tertiary boundary,[448] and that some of today's changes, such as extreme pollution and fragmentation of the land by humans, have no historical or prehistorical precedent.[449] The availability of large-scale ecological data makes it possible to visualize the ways that land use changes have gradually pushed back the boundaries of natural areas.[450]

History provides many other examples of human-caused disturbance that caused the collapse of ecological systems, many of which were not understood until it was too late.[451] Loss of resiliency has led to the collapse of fisheries, the desertification of arable land, the eutrophication of previously clear lakes, and other types of ecological collapse.[452] Many ecologists believe that there is an urgent need to identify and agree upon measurable criteria for limiting the nature and extent of ecological change.[453] Advances in

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447. *See, e.g.*, PETER WARD, THE END OF EVOLUTION: A JOURNEY IN SEARCH OF CLUES TO THE THIRD MASS EXTINCTION FACING PLANET EARTH (1994).

448. John Harte, *Land Use, Biodiversity, and Ecosystem Integrity: The Challenge of Preserving Earth's Life Support System*, 27 ECOLOGY L.Q. 929, 961-63 (2001). *See* David M. Raup, *Extinction in the Geologic Past, in* ORIGINS AND EXTINCTIONS 109 (Donald E. Osterbrock & Peter H. Raven eds., 1988).

449. Christensen et al., *supra* note 134, at 675-76 (1996).

450. For examples, see the website of the National Aeronautic and Space Agency *available at* http://gcmd.gsfc.nasa.gov (last visited Jan. 4, 2002). A list of other sources of such data are *available at* http://www.sciencemag.org/feature/data/ecology2001.shtml (last visited Jan. 4, 2002).

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> For instance the demand for fuelwood can be satisfied by a forest even when the recovery of trees is no longer possible but the subsequent deforestation will be visible some years after the decline start[s] and will probably be discovered too late for countermeasures. The same has occurred in most European uplands over the last fifty years. During this time, the emigration of a considerable part of the population from hilly and mountainous regions occurred, the long term consequence of which was agricultural abandonment. This effect was under-estimated because it was buffered by the older generations of farmers who remained in the countryside, and by huge agricultural subsidies.

ALMO FARINA, LANDSCAPE ECOLOGY IN ACTION 163 (2000). Europeans, having inhabited their continent longer than Americans, may be more conscious of the extent to which human activities can cause ecological collapse. *See* Z. Naveh, *Mediterranean Uplands as Anthropogenic Perturbation-Dependent Systems and Their Dynamic Conservation Management, in* TERRESTRIAL AND AQUATIC ECOSYSTEMS: PERTURBATION AND RECOVERY 545, 548-50 (Oscar Ravera ed., 1991) (describing the rapid decline of Mediterranean habitats).

452. Simon A. Levin, *Multiple Scales and the Maintenance of Biodiversity*, 3 ECOSYSTEMS 498, 502 (2000).

453. The development of such criteria may require more baseline data gathering. *See* H. JOHN HEINZ III CENTER FOR SCIENCE, ECONOMICS AND THE ENVIRONMENT, DESIGNING A

information technology have made the prospect of resolving these issues seem more optimistic today than even a decade ago.[454]

But to resolve these problems caused by the cumulative effects of unidirectional, incremental change, society must undertake measures to reverse trends that are well entrenched[455] and involve the cumulative effect of millions of individual activities, the impact of any one of which may seem innocuous.[456] Two trends that provide examples of gradual, unidirectional change caused by millions of individual human actions are the increased emission of greenhouse gases and the increase in nitrogen deposition in coastal waters.

i. Unidirectional Climate Change

A prominent example of unidirectional change is the response of ecological systems to climate change, a global scale phenomenon that also demands study at extensive temporal scales.[457] Each year in the 1990s ranked among the warmest fifteen years of the Twentieth Century,[458] and the year 2001 was the second warmest year in history.[459]

REPORT ON THE STATE OF THE NATION'S ECOSYSTEMS (1999). For a recent example of baseline data gathering, see Daily at al., *supra* note 275, at 1.

454. Daniel C. Esty & Marian R. Chertow, *Thinking Ecologically: An Introduction, in* THINKING ECOLOGICALLY: THE NEXT GENERATION OF ENVIRONMENTAL POLICY 1, 5 (Marian R. Chertow & Daniel C. Esty eds., 1997).

455. The human modifications of the environment that affect plants include "levels of soil nitrogen, phosphorus, calcium and pH, atmospheric CO_2, herbivore, pathogen, and predator densities, disturbance regimes, and climates." David Tilman & Clarence Lehman, *Human-Caused Environmental Change: Impacts on Plant Diversity and Evolution*, 98 PROC. NAT'L ACAD. SCI. USA 5433, 5433 (2001).

456. *See* James Salzman, *Beyond the Smokestack: Environmental Protection in the Service Economy*, 47 UCLA L. REV. 411, 454-71 (1999) (discussing cumulative impact of small service operations).

457. NAT'L RESEARCH COUNCIL, *supra* note 7, at 27-31. Changes in atmospheric carbon dioxide can be evaluated in the context of 220,000 year record obtained from bubbles in polar ice caps. SCHLESINGER, *supra* note 445, at 11.

458. NATIONAL ASSESSMENT SYNTHESIS TEAM, UNITED STATES GLOBAL CHANGE RESEARCH PROGRAM, CLIMATE CHANGE IMPACTS ON THE UNITED STATES: THE POTENTIAL CONSEQUENCES OF CLIMATE VARIABILITY AND CHANGE 12 (2001), *available at* http://www.usgcrp.gov/usgcrp/nacc/default.htm (last visited May 28, 2002).

459. NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, NATIONAL CLIMATIC DATA CENTER, CLIMATE OF 2001 - ANNUAL REVIEW, *available at* http://lwf.ncdc.noaa.ov/oa/climate/research/2001/ann/ann.html (last updated Jan. 16, 2002).

Unusual weather events of the 1990s [460] brought increasing attention to the need to distinguish historic cycles from unidirectional changes caused by human activity.[461] Current concerns about climate change[462] underscore the need to view ecological phenomena as fluid.[463] Climatologists forecast that many parts of the world will show significant temperature increases over the next century.[464] A committee of the National Academy of Sciences of the United States, in its review of the work of the International Panel on Climate Change, agreed with the Panel's conclusion that the best existing models suggest that temperatures would increase from 2.5 to 10.4 degrees Fahrenheit by the end of the century and that the "predicted warming is larger over higher latitudes than over low latitudes, especially during winter and spring, and larger over land than over sea."[465] The following table illustrates the potential effect of such changes by showing how the

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460. Of particular relevance is the exceptionally strong El Niño event of 1997-1998. *See generally* EL NIÑO 1997-1998: THE CLIMATE EVENT OF THE CENTURY (Stanley A. Chagnon ed., 2000). Historical research indicates that El Niño is a cyclical phenomenon. Periodically, for reasons that have yet to be fully explained, the trade winds disappear and an El Niño condition develops. The air pressure pattern reverses itself, and because there are no trade winds to move the air from the east to the west, the air stays in place and grows warmer. It reaches the point of deep convection, which is the point at which steamy surface air bursts into the upper atmosphere. Water in the upper atmosphere condenses and falls on the west coast of the Americas as torrential rain. This leads to many other changes. While the Americas experience an increase in rainfall, Australia, Indonesia, and India often experience drought. In North America, the jet streams shift, and the polar jet stream generally stays over Canada, resulting in less cool air over the U.S. Upper level tropical winds also reverse themselves, which takes the tops off cyclones forming in the mid-Atlantic. The number of hurricanes that hit the U.S. tends to be cut in half. ROGER G. BARRY & RICHARD J. CHORLEY, ATMOSPHERE, WEATHER AND CLIMATE 276-82 (7th ed. 1998).

461. Paleoecologists study the impact of weather cycles on organisms at geological time scales. *See* Mats Dynesius & Roland Jansson, *Evolutionary Consequences of Changes in Species' Geographical Distributions Driven by Milankovitch Climate Oscillations*, 97 PROC. NAT'L ACAD. SCI. USA 9115 (2000). *See generally* SCHLESINGER, *supra* note 445.

462. I have summarized my analysis of the climate change issue in FRED BOSSELMAN ET AL., ENERGY, ECONOMICS AND THE ENVIRONMENT 1200, 1200-41 (2000).

463. *See, e.g.*, Robert T. Paine et al., *Compounded Perturbations Yield Ecological Surprises*, 1 ECOSYSTEMS 535, 537-38 (1998) (stating that climate change increases impact of environmental disturbance); Turner & Dale, *supra* note 342, at 758 (1997) ("Understanding the response of disturbance regimes characterized by large, infrequent events to climatic change remains an important challenge.").

464. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, SUMMARY FOR POLICYMAKERS: A REPORT OF WORKING GROUP I OF THE IPCC (2001), *at* www.usgcrp.gov/ipcc.htm (updated Aug. 3, 2000); INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2001: THE SCIENTIFIC BASIS–SUMMARY FOR POLICYMAKERS, A REPORT OF WORKING GROUP I OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (2001), *at* www. sgcrp.gov/usgcrp/assessments. tmipcc/htm (updated Feb 5, 2002).

465. COMMITTEE ON THE SCIENCE OF CLIMATE CHANGE, DIVISION OF EARTH AND LIFE STUDIES, NATIONAL RESEARCH COUNCIL, CLIMATE CHANGE SCIENCE: AN ANALYSIS OF SOME KEY QUESTIONS 4 (2001). For a general overview of climate change science, see FRANCES DRAKE, GLOBAL WARMING: THE SCIENCE OF CLIMATE CHANGE (2000).

average temperature in certain cities might come to resemble the current average temperature in other, warmer cities:

CITIES WITH ANNUAL MEAN TEMPERATURES ILLUSTRATIVE OF POTENTIAL INCREASED WARMING[466]

Current city	3-4 degree F. increase	6-7 degree increase	9-10 degree F. increase
Winnipeg	Quebec	Montreal	Toronto
Bismarck	Sioux Falls	Toledo	Columbus OH
Burlington VT	Youngstown	Boston	Wilmington DE
Buffalo	Pittsburgh	Philadelphia	Paducah
Denver	Topeka	Amarillo	Charlotte
Chicago	Indianapolis	Asheville	Washington DC
Portland OR	San Francisco	Tulsa	Fresno
New York City	Washington DC	Birmingham	Jackson MS
St. Louis	Oklahoma City	Columbia SC	Shreveport
San Francisco	Sacramento	Fresno	Waco
Nashville	Wichita Falls	Dallas	Austin
Atlanta	Columbus GA	Jacksonville	Daytona Beach
El Paso	Tallahassee	Galveston	Tampa
Los Angeles	Galveston	Orlando	Miami
New Orleans	Corpus Christi	West Palm Beach	Honolulu
Austin	Phoenix	Kahului	Key West

It will be particularly important to try to predict the impact of this warming on ecological systems.[467] Studies of the impact of

466. Annual mean temperatures for United States cities taken from NATIONAL CLIMATIC DATA CENTER, COMPARATIVE CLIMATIC DATA FOR THE UNITED STATES THROUGH 1999 95-102 (2000); Canadian data taken from GILBERT SCHWARTZ, THE CLIMATE ADVISOR 253-90 (1977); table compiled by author.

467. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, WORKING GROUP II, CLIMATE

climate change on animal species are already beginning to show significant geographical movements of animals that appear to be the result of changes in climate.[468] For example, amphibians in Costa Rican cloud forests have significantly declined in the face of warmer and drier conditions.[469] A study of thirty-four European butterfly species found that their ranges had shifted to the north from 35 to 240 kilometers.[470]

The impact of climate change has been most notable in the northern part of the northern hemisphere. Rapid temperature increases in the Arctic regions[471] have had significant impacts on the species there[472] and models anticipate even greater future temperature increases[473] and ecological change.[474]

CHANGE 2001: IMPACTS, ADAPTATION AND VULNERABILITY, *at* http://usgcrp.gov/usgcrp/assessments.htm (updated Feb. 5, 2002).

468. *See, e.g.*, Jeremy T. Kerr, *Butterfly Species Richness Patterns in Canada: Energy, Heterogeneity, and the Potential Consequences of Climate Change*, 5 CONSERVATION ECOLOGY 1, 10, *available at* www.consecol.org/vol5/iss1/art10. For reviews of these studies, see John P. McCarty, *Ecological Consequences of Recent Climate Change*, 15 CONSERVATION BIOLOGY 320 (2001); Josep Peñuelas & Iolanda Filella, *Responses to a Warming World*, 294 SCIENCE 793 (2001).

469. J. Alan Pounds et al., *Biological Response to Climate Change on a Tropical Mountain*, 398 NATURE 611 (1999). South African ecologists are also worried that warmer and drier conditions may have massive impact on the highly diverse fynbos region in the Cape Province. W.J. Bond, *Functional Types for Predicting Changes in Biodiversity: A Case Study in Cape Fynbos, in* PLANT FUNCTIONAL TYPES: THEIR RELEVANCE TO ECOSYSTEM PROPERTIES AND GLOBAL CHANGE 174, 188 (T.M. Smith et al. eds., 1997).

470. Bernice Wuethrich, *How Climate Change Alters the Rhythms of the Wild*, 287 SCIENCE 793, 795 (2000). For an analysis of the impact of climate change on the mosquitoes that carry malaria, see S.I. Hay et al., *Climate Change and the Resurgence of Malaria in the East African Highlands*, 415 NATURE 905 (2002).

471. CLIMATE CHANGE IMPACTS ON THE UNITED STATES, *supra* note 458, at 287. (noting that Alaska's climate has warmed about 4 degrees Fahrenheit since the 1950s - part of a larger Arctic trend); For an interesting study of warming trends based on the results of an Alaskan ice break-up contest that has been held since 1917, see Raphael Sagarin & Florenza Micheli, *Climate Change in Nontraditional Data Sets*, 294 SCI. 811 (2001).

472. Kerr, *supra* note 468, at 10 (noting that many butterfly species throughout Canada appear to have expanded their range northward); C.D. Keeling et al., *Increased Activity of Northern Vegetation Inferred from Atmospheric Co_2 Measurements*, 382 NATURE 146 (1996) (pointing out the longer growing season for Arctic plants); Cynthia T. Tynan et al., *Endangered Right Whales on the Southeastern Bering Sea Shelf*, 294 SCI. 1894 (2001) (noting that right whales are at risk from warming waters). *See also* William Stolzenburg, *Nature Feels the Heat: As Climate Goes Awry, Wildlife Goes Away*, 51 NATURE CONSERVANCY 12, 17-18 (2001), *available at* http://nature.org/aboutus/magazine/2001/sepoct/work/art4735.html (discussing how the Nature Conservancy is trying to react to the impact of warming temperatures on their northern reserves); Darcy Frey, *George Divoky's Planet*, N.Y. TIMES MAG., Jan. 6, 2002, at 24 (discussing Divoky's study of how birds in the Beaufort Sea have reacted to warming conditions).

473. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2001: SYNTHESIS REPORT– Summary for Policymakers *available at* http://www.usgcrp.ov/usgcrp/ipcc.htm#SynthesisRrport (updated Feb. 5, 2002) (noting that glaciers are likely to continue widespread retreat, and that Northern Hemisphere snow cover, permafrost, and sea-ice extent are projected to decrease further).

474. T. Scott Rupp et al., *Response of Subarctic Vegetation to Transient Climatic Change*

Plant species will also be significantly affected by climate change.[475] Increased levels of carbon dioxide accelerate plant growth in laboratory studies,[476] but many botanists believe that any stimulative effects will be offset by declines in soil nutrient availability.[477] Moreover, the plants that could readily adapt to the new climate conditions may be far away and lack good dispersal capability.[478] And although some scientists hope that higher carbon dioxide levels will increase the ability of forests to store carbon, recent studies cast doubt on the extent to which this will occur.[479]

Not all climate change is unidirectional. The ability to study the world's climate at large temporal and spatial scales has led to a

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on the Seward Peninsula in Northwest Alaska, 6 GLOBAL CHANGE BIOLOGY 541, 552-53 (2000), *available at* http://www.blackwell-synergy.com/servlet/useragent?func=callWizard&wizardKey=salesAgent: 1013562618390&action=show (showing that tundra would be replaced by forest with frequent fires). The World Wildlife Fund predicts that as much as 70% of the natural habitat of the Arctic could be lost by the end of the century. Sarah Lyall, *A Global Warming Report Predicts Doom for Many Species*, N.Y. TIMES, Sept. 1, 2000, at A3. *See also* Walter C. Oechel et al., *Effects of CO_2 and Climate Change on Arctic Ecosystems, in* ECOLOGY OF ARCTIC ENVIRONMENTS 255 (Sarah J. Woodin & Mick Marquiss eds., 1997). The Arctic is also the area most susceptible to pollution from many organic pollutants that vaporize in warmer climates but condense when they encounter colder temperatures. Chemicals such as DDT, PCBs, chlordane, and dioxin flow throughout the world's atmosphere, reaching the surface primarily in the polar regions. Concentrations of these substances build up to dangerous levels in the fat tissues of Arctic animals. Indigenous peoples of the region tend to eat substantial amounts of animal fats, and this has produced significant concerns about long term effects on human health in the Arctic regions. One example is a monitoring program sponsored by a number of northern countries, *available at* http://www.amap.no (last visited Jan. 5, 2002). A convention signed in 2001 establishes procedures for the international regulation of these substances. Peter L. Lallas, *The Stockholm Convention on Persistent Organic Pollutants*, 95 AM. J. INT'L L. 692 (2001).

475. Tilman & Lehman, *supra* note 455.

476. CHARLES J. KREBS, ECOLOGY: THE EXPERIMENTAL ANALYSIS OF DISTRIBUTION AND ABUNDANCE 681-83 (4th ed. 1994).

477. Increased CO_2 resulting from climate change will cause little increased growth stimulation except where soil nitrogen is abundant, but even then the increase "will be constrained by declines in the nutrient availability due to the increased C/N ratio of plant litter, resulting in greater nitrogen immobilization by soil microbes." S.E. Hobbie et al., *Resource Supply and Disturbance as Controls over Present and Future Plant Diversity, in* BIODIVERSITY AND ECOSYSTEM FUNCTION 385 (Ernst-Detlef Schulze & Harold A. Mooney eds., 1994). One recent study suggests that areas with a rich diversity of species will more effectively store the carbon generated by faster plant growth than will species-poor areas, such as agricultural monocultures. Peter B. Reich et al., *Plant Diversity Enhances Ecosystem Responses to Elevated CO_2 and Nitrogen Deposition*, 410 NATURE 809 (2001).

478. D. Tilman, *Community Diversity and Succession: The Roles of Competition, Dispersal, and Habitat Modification, in* BIODIVERSITY AND ECOSYSTEM FUNCTION 327, 339 (Ernst-Detlef Schulze & Harold A. Mooney eds., 1994); David S. Woodruff, *Declines of Biomes and Biotas and the Future of Evolution*, 98 PROC. NAT'L ACAD. SCI. USA 5471, 5472 (2001) (noting that the ability of plants to adapt is reduced by creation of inhospitable matrix between habitat patches).

479. *See, e.g.*, William H. Schlesinger & John Lichter, *Limited Carbon Storage in Soil and Litter of Experimental Forest Plots Under Increased Atmospheric CO_2*, 411 NATURE 466 (2001); Ram Oren et al., *Soil Fertility Limits Carbon Sequestration by Forest Ecosystems in a CO_2-enriched Atmosphere*, 411 NATURE 469 (2001).

greater understanding of the cyclical nature of certain climatic patterns.[480] Much attention has been focused on the cycle of temperature change of the waters of the South Pacific known as the El Niño Southern Oscillation (ENSO).[481] A recent example is the El Niño of 1997-98, which dramatically altered weather patterns around the world, causing at least 2100 deaths and approximately $33 billion in property damage.[482] Numerous recent studies have examined the effects on the ENSO cycles on the plants and animals in the affected areas.[483] The ability to predict ENSO cycles remains elusive.[484]

Cycles of rainfall and drought are also seen as a natural part of ecological processes. Nowhere has this been more evident than in the Everglades, where ecologists and engineers are trying to protect ecological systems of staggering complexity. For example, the wood stork only nests in the Everglades when water levels are low. The snail kite only nests when water levels are high. Both species are threatened.[485]

Through large scale studies we may improve our ability to separate the impacts of cyclical climate change from the impacts of

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480. For a concise summary of climate change analysis, see BARRY & CHORLEY, *supra* note 460, at 42.

481. *See generally* EL NIÑO, *supra* note 460. The phenomenon of El Niño has captured the public attention only recently, although historians and archaeologists have been able to reconstruct evidence indicating that the phenomenon has long existed. Fishermen originally gave this weather phenomenon its name. A pool of hot water the size of Canada would appear off the west coast of the Americas around Christmastime, so the fishermen gave it the name El Niño for Christ Child. There are records of El Niño's effects on Peru as far back as 1525 and it is possible that the Incas knew of El Niño 13,000 years ago. However, the rest of the world only started paying attention to this climate cycle about twenty-five years ago. Curt Suplee, *El Niño / La Niña, Nature's Vicious Cycle*, 195 NAT'L GEOGRAPHIC, Mar. 1999, at 72.

482. Suplee, *supra* note 481, at 73.

483. *See, e.g.*, P.D. Plisnier et al., *Impact of ENSO on East African Ecosystems: A Multivariate Analysis Based on Climate and Remote Sensing Data*, 9 GLOBAL ECOLOGY & BIOGEOGRAPHY 481 (2000). A review of such studies is found in Milena Holmgren et al., *El Niño Effects on the Dynamics of Terrestrial Ecosystems*, 16 TRENDS IN ECOLOGY & EVOLUTION 89 (2001); Fabian M, Jaksic, *Ecological Effects of El Niño in Terrestrial Ecosystems of Western South America*, 24 ECOGRAPHY 241 (2001). Research into deep ocean currents may uncover further links between oceanic oscillations and climate. William K. Stevens, *Scientists Studying Deep Ocean Currents for Clues to Climates*, N.Y. TIMES, Nov. 9, 1999, at F5.

484. NAT'L RESEARCH COUNCIL, *supra* note 7, at 28.

485. Harris, *supra* note 172, at 319, 327. *See also* Simberloff, *supra* note 193, at 247, 251 (noting that the endangered Devil's Hole pupfish is favored by managers who keep water levels at heights that threaten a listed insect, the Ash meadows naucorid); Holly Doremus, *The Rhetoric and Reality of Nature Protection: Toward a New Discourse*, 57 WASH. & LEE L. REV. 11, 62 (2000) (noting that efforts to prevent invasive salt cedar from outcompeting native vegetation have been difficult because endangered bird has begun nesting in salt cedar).

long-range climate change[486] that are most worrisome to ecologists.[487] Because the effects of increased greenhouse gases are not likely to be cyclical,[488] the adaptations that plants have developed to cope with cyclical climatic variation may not be successful for adjusting to a steady change in one direction.[489] Ecologists are learning more about the impact of cyclical climate change, while faced with the probability of continuing unidirectional change toward warmer conditions that seem to defy easy metastable solutions.[490] Ecologists have begun to explore whether we can redesign our methods for protecting natural areas to cope with the changing climate. Flexible location of reserve boundaries is an appealing idea in principle, although it "has little precedent in the real world," but corridor systems that connect natural areas may become particularly important, because difficulty of dispersal to new habitats may be " the single biggest barrier to ecosystem adaptation in a changing climate."[491]

ii. Nitrogen Deposition

The lands and waters of the United States have been receiving increased quantities of nitrogen originating from human sources.[492] A group of leading ecologists led by Stanford's Peter Vitousek recently opined that: "[H]uman alterations of the nitrogen cycle have (1) approximately doubled the rate of nitrogen input into the

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486. *See* Thomas Kitzberger et al., *Inter-hemispheric Synchrony of Forest Fires and the El Niño-Southern Oscillation*, 10 GLOBAL ECOLOGY & BIOGEOGRAPHY 315 (2001); Lance Gunderson, *Resilience, Flexibility and Adaptive Management – Antidotes for Spurious Certitude?*, 3 CONSERVATION ECOLOGY 7, *available at* http://www.consecol.org/vol3/iss1/art7.

487. For a review of recent studies, see John P. McCarty, *Ecological Consequences of Recent Climate Change*, 15 CONSERVATION BIOLOGY 321 (2001).

488. INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, *supra* note 473 (noting that stabilization of carbon dioxide in the atmosphere requires eventual reduction of global emissions to a small fraction of the current emission level). A series of case studies that examine the impact of climate change on ecological processes is found in WILDLIFE RESPONSES TO CLIMATE CHANGE: NORTH AMERICAN CASE STUDIES (Stephen H. Schneider & Terry l. Root eds., 2002).

489. Tilman, *supra* note 478, at 335-36.

490. *See, e.g.*, Tilman & Lehman, *supra* note 455.

491. Adam Markham & Jay Malcolm, *Biodiversity and Wildlife: Adaptation to Climate Change*, *in* ADAPTING TO CLIMATE CHANGE: AN INTERNATIONAL PERSPECTIVE 384, 392-93 (Joel B. Smith et al. eds., 1996). The Nature Conservancy has been studying ways of adapting its reserve system to climate change. Carol Goodstein, *A Sea Change: As the Planet Warms, The Nature Conservancy Searches for New Strategies*, 51 NATURE CONSERVANCY 22 (2001).

492. For a general description of the problems of managing nutrient loading of waters, see Clive A. David, *Managing the Invisible: Ecosystem Management and Macronutrient Cycling*, *in* ECOSYSTEM MANAGEMENT: APPLICATIONS FOR SUSTAINABLE FOREST AND WILDLIFE RESOURCES 94 (Mark S. Boyce & Alan Haney eds., 1997). Increased nitrogen loading impacts terrestrial ecological systems as well. *See generally* Tilman & Lehman, *supra* note 455, at 5436-38.

terrestrial nitrogen cycle, with the rates still increasing; . . . [and] (5) greatly increased the transfer of nitrogen through rivers to estuaries and coastal oceans."[493] This increased spread of nitrogen, primarily from the use of fertilizers and the burning of fossil fuels,[494] is harming ecological systems and threatening public health.[495]

The failure to undertake control of nonpoint sources of nitrogen and phosphorus has resulted in a steady increase in the nutrient loading of coastal waters.[496] As the National Research Council recently pointed out, the "results of excessive nutrient loadings are seen in reduced water clarity; nuisance algal blooms, including species with toxic forms . . ., and hypoxic (low oxygen) bottom waters." The "decomposition of dead algae in bottom waters consumes oxygen, leading to loss of habitat for fish and other forms of life."[497]

For example, leakage from injection of waste into wells in the Florida Keys has caused substantial eutrophication in and around Florida Bay.[498] In some cases, eutrophication results in algal blooms that can be harmful to human health.[499] The various

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493. Peter M. Vitousek et al., *Human Alteration of the Global Nitrogen Cycle: Sources and Consequences*, 7 ECOLOGICAL APPLICATIONS 737 (1997). *See also* Thomas E. Jordan & Donald E. Weller, *Human Contributions to Terrestrial Nitrogen Flux*, 46 BIOSCIENCE 655 (1996).

494. The nitrogen compounds released from the tall stacks of coal-burning power plants are a major source of acid rain. SCHLESINGER, *supra* note 445, at 387-88.

495. Jocelyn Kaiser, *The Other Global Pollutant: Nitrogen Proves Tough to Curb*, 294 SCI. 1268 (2001). The agricultural industry refers to this process as "nutrient enrichment." Oliver A. Houck, *Damage Control: A Field Guide to Important Euphemisms in Environmental Law*, 15 TUL. ENVTL. L.J. 129, 131 (2001).

496. *See* David Tilman, *The Greening of the Green Revolution*, 396 NATURE 211 (1998) (noting that conventional agriculture releases more nitrogen than alternative methods such as reduced tillage or manure application). For an analysis of the impact of nitrogen deposition on the Great Barrier Reef, see Miles Furnas & Alan Mitchell, *Runoff of Terrestrial Sediment and Nutrients into the Great Barrier Reef World Heritage Area*, *in* OCEANOGRAPHIC PROCESSES OF CORAL REEFS: PHYSICAL AND BIOLOGICAL LINKS IN THE GREAT BARRIER REEF 37, 42-46 (Eric Wolanski ed., 2001).

497. NAT'L RESEARCH COUNCIL, *supra* note 3, at 84. *See also* U.S. EPA, OFFICE OF WATER, NATIONAL WATER QUALITY INVENTORY: 1998 REPORT TO CONGRESS 130-32 (1998), available at www.epa.gov/305b/98report/toc.html. David Tilman, *Global Environmental Impacts of Agricultural Expansion: The Need for Sustainable and Efficient Practices*, 96 PROC. NAT'L ACAD. SCI. USA 5995 (1999) (noting that the impacts of nitrogen and phosphorus are well documented). Ironically, the increased deposit of nitrogen to the soil is believed to increase the ability of the terrestrial ecological systems to absorb carbon dioxide from the air. NAT'L RESEARCH COUNCIL, *supra* note 7, at 15.

498. Sydney T. Bacchus, *Knowledge of Groundwater Responses: A Critical Factor in Saving Florida's Threatened and Endangered Species*, 18 ENDANGERED SPECIES UPDATE 79, 81 (2001).

499. Lora E. Fleming et al., *Emerging Harmful Algal Blooms and Human Health: Pfiesteria and Related Organisms*, 27 TOXICOLOGIC PATHOLOGY 573 (1999). The increasing frequency and severity of algal blooms also impacts ecological systems. Bruce McKay & Kieran Mulvaney, *A Review of Marine Major Ecological Disturbances*, 18 ENDANGERED SPECIES

governmental agencies surrounding Chesapeake Bay have also been working for years to reduce the excessive nitrogen loadings,[500] but progress is slow.[501]

Where nitrogen loading is heavy, the oxygen content of water can be depleted ("hypoxia") or eliminated ("anoxia").[502] The largest area of environmental damage from increased nitrogen is an extensive area in the Gulf of Mexico where lower levels of the gulf waters are deprived of adequate oxygen every summer.[503] Between 1993 and 1998 the size of the so-called "dead zone" ranged from about 12,500 to about 18,000 square kilometers.[504]

The severity of hypoxic conditions, apparently varying with the extent of the Mississippi River discharge into the Gulf, reached a peak after the 1993 floods on the River.[505] One computer model has projected that continuing climate change will continue to produce

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UPDATE 14 (2001). *See also* JoAnn M. Burkholder, *Eutrophication and Oligotrophication, in* 2 ENCYCLOPEDIA OF BIODIVERSITY 649, 655-58 (Simon A. Levin ed., 2001).

500. Robert Costanza & Jack Greer, *The Chesapeake Bay and Its Watershed: A Model for Sustainable Ecosystem Management, in* ECOSYSTEM HEALTH 261 (David Rapport et al. eds., 1998).

501. Francis X. Clines, *Progress in Cleaning Chesapeake Bay, but Far to Go*, N.Y. TIMES, July 22, 2001, § 1, at 16.

502. JoAnn M. Burkholder, *Eutrophication and Oligotrophication, in* 2 ENCYCLOPEDIA OF BIODIVERSITY 649, 652 (Simon A. Levin ed., 2001).

503. The Science Museum of Minnesota has an interactive web site that illustrates the phenomenon of this "dead zone," *at* http://www.smm.org/DeadZone/top.html (last visited Sept. 17, 2001).

504.
> The largest zone of oxygen-depleted coastal waters in the United States, and the entire western Atlantic Ocean, is found in the northern Gulf of Mexico on the Louisiana and Texas continental shelf, influenced by the freshwater and nutrient flux of the Mississippi River system. Hypoxia covers broad regions of the shelf for extended periods in mid-summer. The mid-summer extent of hypoxic waters between 1985 and 1992 averaged 8,000 to 9,000 km2 but increased to between 16,000 and 18,000 km2 from 1993 to 1997. The prevailing oceanographic conditions in 1998 reduced the hypoxic zone to 12,480 km2. Low oxygen has been documented as early as February and as late as October, but is most widespread, persistent and severe from May to September in water depths of five to thirty meters. Hypoxia occurs mostly in the lower water column but may encompass as much as the lower half to two-thirds of the total water column. Continuous time-series data for the bottom waters in the core of the hypoxia region show (1) the gradual decline in oxygen in the spring with interruptions due to wind-mixing events, (2) persistent and severe hypoxia and anoxia for extended parts of the record from May to October, (3) occasional summer upwelling of oxygenated water from the outer shelf, and (4) the seasonal disruption of low oxygen in the fall from tropical storms or cold fronts.

Nancy N. Rabalais, *Hypoxia in the Gulf of Mexico*, 12 TUL. ENVTL. L.J. 321, 321-22 (1999) (footnotes omitted).

505. Mary L. Belefski & Larinda Tervelt Norton, *Hypoxia in the Gulf of Mexico: A Historical and Policy Perspective*, 12 TUL. ENVTL. L. J. 331, 337 (1999). A certain amount of nitrogen discharge is essential to the Gulf fisheries, but the growing hypoxia could adversely affect shrimp populations. *Id.* at 338.

heavier outflows from the Mississippi River and will increase the spread of the hypoxic area in both in space and time.[506]

Nitrogen originates from many natural sources as well as from human activities,[507] but the increasingly heavy applications of inorganic nitrogen-based fertilizer by farmers in the Mississippi watershed appear to be responsible for much of the increase.[508] Congress enacted legislation in 1998 directing the Office of Science and Technology Policy to develop a plan to address the hypoxia problem.[509]

Increased nitrogen discharge to coastal waters is widely recognized to be a worldwide problem.[510] The impact of nitrogen loadings on coastal waters of other countries is continuing inexorably, with the North Sea, the Black Sea, and the Baltic Sea, in particular, receiving a steadily growing nitrogen load.[511] In the

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506. Dubravko Justić et al., *Effects of Climate Change on Hypoxia in Coastal Waters: A Doubled CO_2 Scenario for the Northern Gulf of Mexico*, 41 LIMNOLOGY & OCEANOGRAPHY 992, 1001-02 (1996).

507. Long-term data that would document the occurrence of hypoxia earlier than the 1970s do not exist. Sediment cores from the Mississippi River bight provide surrogates for historical conditions in overlying waters and the benthic habitat. While century-long changes are evident in some of the retrospective analyses, the most dramatic and accelerating changes have occurred since the 1950s, when nitrogen loads began to increase and eventually doubled over their historic values . . . . Evidence associates oxygen depletion with changes in landscape use and nutrient management that result in nutrient enrichment of receiving waters. Nutrient flux in coastal systems, while essential to the overall productivity of those systems, has increased over time due to anthropogenic activities and has led to broad-scale degradation of the marine environment.

Rabalais, *supra* note 504, at 325-26 (footnotes omitted).

508. The most noticeable change in human activity in the watershed since the 1950s is in fertilizer application rates and changes in land use that affect the fate and transformation of nutrients before they reach the Gulf of Mexico. Animal husbandry practices have shifted to higher intensity operations. A small percentage of atmospheric nitrogen reaches the watershed, but it has likely increased over time. Wastewater treatment effluent is a small percentage of the nitrogen load. Efforts to manage nutrients should focus on those aspects of landscape architecture and human activities that show a documented effect in increasing eutrophication and worsening oxygen stress and on those that can be controlled.

Id. at 326 (1999) (footnotes omitted). The agricultural industry would of course expect to be subsidized for any reductions in nitrogen discharge. Belefski & Norton, *supra* note 505, at 347-48.

509. Pub. L. No. 105-383, § 601, 112 Stat. 3411, 3447 (1998). *See* Belefski & Norton, *supra* note 505, at 344-45.

510. For a UNEP summary of nitrogen loading issues, see www.unep.org/Geo2000/english/0036.htm (last visited Sept. 17, 2001).

511. DON HINRICHSEN, COASTAL WATERS OF THE WORLD: TRENDS, THREATS AND STRATEGIES 50, 58, 67 (1998); Sandy L. Tartowski & Robert W. Howarth, *Nitrogen, Nitrogen Cycle*, *in* 4 ENCYCLOPEDIA OF BIODIVERSITY 377, 381 (Simon A. Levin ed., 2001).

Baltic Sea, anoxic conditions in the lower layer of water cover an area of about 100,000 square kilometers for at least part of every year, resulting in dramatic declines in fish stocks.[512]

A further implication of increased human dispersal of nitrogen is a growing presence in the atmosphere of nitrous oxide (N_2O), a greenhouse gas that is about 300 times as powerful as carbon dioxide.[513] Recent studies suggest placing heavy emphasis on reducing especially powerful greenhouse gases such as nitrous oxide.[514] Currently extensive research is underway to try to find means of slowing the rate of nitrous oxide dispersion, which appears to be increasing at about 0.3% per year.[515]

iii. Reduction of Resource Availability

One of the common measures of ecological processes is "productivity," which relates to the amount of the sun's energy that is used to fix atmospheric carbon dioxide.[516] Some disturbances increase productivity by increasing resource availability. After a fire, for example, nutrients that were formerly in the living biomass become available as nutrients to plants and other organisms.[517] But at the reorganization stage, because the "system is underconnected, with weak organization and weak regulation," it is unstable, and chance events may allow a different species – perhaps an "exotic invader" – to become established.[518]

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512. KENNETH H. MANN, ECOLOGY OF COASTAL WATERS WITH IMPLICATIONS FOR MANAGEMENT 163 (2d ed. 2000).

513. SCHLESINGER, *supra* note 445, at 394. This problem was noted a decade ago in JONATHAN WEINER, THE NEXT ONE HUNDRED YEARS: SHAPING THE FATE OF OUR LIVING EARTH 50-51 (1990).

514. James Hansen et al., *Global Warming in the Twenty-First Century: An Alternative Scenario*, 97 PROC. NAT'L ACAD. SCI. USA 9875 (2000).

515. SCHLESINGER, *supra* note 445, at 10, 203, 393-96.

516. For a concise and readable account of the process, see E.C. PIELOU, THE ENERGY OF NATURE 116 *et. seq.* (2001). The standard methods of measuring productivity are discussed in NAT'L RESEARCH COUNCIL, *supra* note 3, at 90-102.

517. Holling refers to these processes of disturbance and reorganization as "creative destruction," and emphasizes that it is these processes that determine whether the ecological system can get back into the previous cycle or whether it collapses. C.S. Holling, *The Resilience of Terrestrial Ecosystems, in* THE DEVELOPMENT OF ECOLOGICAL ECONOMICS 107, 120-24 (Robert Costanza et al. eds., 1997). Holling refers to the third phase of the cycle as "creative destruction" with a bow to the economist, Joseph Schumpeter, who used that phrase to characterize capitalism.

518. Holling, *supra* note 335, at 65-66 (citing the rampant growth of Melaleuca in the Everglades as an example of exotic species that became dominant after human-caused disturbance). At the reorganization stage, when the system is weakly organized, it is most subject to "probabilistic events that allow a diversity of entrained species, as well as exotic invaders, to become established." Holling, *supra* note 139, at 482.

Other disturbances cause loss of resources from the system through, for example, volatilization or erosion,[519] which may lead to the collapse of the ecological system.[520] Pickett and White emphasize that "some disturbances may be so severe as to decrease resource availability or to obliterate the system completely."[521] For example, while natural forest fires typically cause little soil disturbance, extensive timber harvest often causes soil erosion and adversely impacts the character of forest streams.[522] Severe disturbance can also result from more subtle changes. For example, scattered urbanization may eliminate carnivores that were predators of the white-tailed deer, resulting in widespread habitat destruction caused by over-population of deer.[523]

If instability has been extreme, many species may be unable to subsist and the ecological system may collapse.[524] Ecological systems with low biological diversity may be especially susceptible to loss of resiliency.[525] Paleoecologists, who study the past through

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519. Ernst-Detlef Schulze & Harold A. Mooney, *Ecosystem Function of Biodiversity: A Summary, in* BIODIVERSITY AND ECOSYSTEM FUNCTION 497, 497-99 (Ernst-Detlef Schulze & Harold A. Mooney eds., 1994); HUSTON, *supra* note 285, at 227-28. For example, once pasture replaces tropical rainforest, the abandonment of the pasture will not result in a return to the rainforest; rather, a relatively barren landscape is likely to evolve. De Leo & Levin, *supra* note 116, at ¶ 31. *See also* Wayne C. Zipperer et al., *The Application of Ecological Principles to Urban and Urbanizing Landscapes*, 10 ECOLOGICAL APPLICATIONS 685, 685-86 (2000); Holling, *supra* note 139, at 480-81.

520.
> When a system becomes unstable, upper-level constraints cannot maintain the system's current configuration. There are two possible outcomes: either the system collapses to a diffuse, low level of organization; or, alternatively, a new set of upper-level constraints emerge and the system moves to a higher level of organization .... In both cases [what] disappears are the relationships that held the material in some special configuration.

AHL & ALLEN, *supra* note 124, at 171.

521. THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS, *supra* note 331, at 378. "Whether large disturbances are qualitatively different from numerous small disturbances remains an unresolved issue in ecology, in part because of a paucity of long-term data on the effects of large-scale disturbances and the impossibility of replicating such events." Turner & Dale, *supra* note 342, at 758.

522. Dale et al., *supra* note 47, at 653. Soil fertility is crucial. John J. Ewel, *Ecosystem Processes and the New Conservation Theory, in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 252, 259 (Steward T.A. Pickett et al. eds., 1997) ("To sustain biological richness, the abiotic features of the ecosystem must be retained, and in the case of terrestrial ecosystems the most vulnerable abiotic factor is soil fertility").

523. *See generally* Roger C. Anderson, *Native Pests: The Impact of Deer in Highly Fragmented Habitats, in* CONSERVATION IN HIGHLY FRAGMENTED LANDSCAPES 117 (Mark W. Schwartz ed., 1997). Aldo Leopold was one of the first to raise the public's consciousness of this phenomenon. CURT MEINE, ALDO LEOPOLD: HIS LIFE AND WORK 457-59 (1988).

524. Monica G. Turner & Virginia H. Dale, *Comparing Large, Infrequent Disturbances: What Have We Learned?*, 1 ECOSYSTEMS 493, 494 (1998).

525. Dale et al., *supra* note 47, at 650.

ice cores, tree rings, and other such evidence, can identify many examples of such system collapses.[526]

The ability to predict the point at which loss of resiliency would cause ecological collapse would be of great value.[527] Thus resource managers increasingly seek to stabilize disturbances at moderate levels,[528] believing that over time, "species diversity is likely to be maximized when the disturbance pattern resembles that historically characteristic of the community."[529] With that in mind, ecologists recognize the importance of the search for parameters that identify historical boundaries of ecological change.[530]

iv. Exceeding the Parameters of Natural Change

Although current ecology recognizes that change is a part of natural ecological processes, ecologists reject the use of the inevitability of change as an excuse to blindly alter or speed processes of change.[531] Instead, they seek to maintain ecological

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526. RICHARD T.T. FORMAN, LAND MOSAICS: THE ECOLOGY OF LANDSCAPES AND REGIONS 506-09 (1995); Hazel R. Delcourt & Paul A. Delcourt, *Paleoecological Analysis of the Legacy of Past Landscapes*, *in* ISSUES IN LANDSCAPE ECOLOGY 51 (John A. Wiens & Michael R. Moss eds., 1999).

527. Simon A. Levin, *Multiple Scales and the Maintenance of Biodiversity*, 3 ECOSYSTEMS 498, 502 (2000) (In some cases prediction is possible, but in others one must hope that reliance on precautionary principles will be sufficient).

528.
> A system that is in a constant steady state is not a system that is evolving, and therefore is not particularly resilient to a major disturbance of some kind because it is not in an "adaptive" mode. On the other hand, a system that gets so responsive that it is constantly adapting to every tiny input is so agitated that it may slip into chaos. It is the systems that are on the ridge between perfect stability and chaos that may be best situated to adapt to changing circumstances and therefore "improve" themselves over time.

George Frampton, *Ecosystem Management in the Clinton Administration*, 7 DUKE ENVTL. L. & POL'Y FORUM 39, 47 (1996). But Michael Bean expresses concern that this approach to resource management is so open-ended that it resembles the "multiple use" policy of natural resource management that has contributed to today's "conservation crises." Michael J. Bean, *Creating Policy on Species Diversity*, *in* BIODIVERSITY IN MANAGED LANDSCAPES 689, 696 (Robert C. Szaro and David W. Johnson eds., 1996). *See also* NAT'L RESEARCH COUNCIL, *supra* note 227, at 180. The objective of preserving entire ecosystems is not without its critics, in the form of some animal rights groups who argue that protection of natural communities rather than individual species is "ecological fascism" because it places the interest of the group ahead of the interest of the individual animal. TOM REGAN, THE CASE FOR ANIMAL RIGHTS 361-62 (1983).

529. Julie Sloan Denslow, *Disturbance-Mediated Coexistence of Species*, *in* THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS 307, 321 (S.T.A. Pickett and P.S. White, eds., 1985).

530. NAT'L RESEARCH COUNCIL, *supra* note 227, at 111-23 (1995).

531. Michael E. Soulé, *The Social Siege of Nature*, *in* REINVENTING NATURE: RESPONSES TO POSTMODERN DECONSTRUCTION 137, 154-60 (Michael E. Soulé & Gary Lease eds., 1995) (rejecting the argument that since nature is no longer natural, we can do whatever we want to it). *See also* Christensen et al., *supra* note 134, at 675 (pointing out that logging, for example, only superficially resembles the effects of fire on a forest).

processes by keeping change within its historical range of variability.[532] Increasingly, ecologists are concerned that the steady increase in the human alteration of natural environments is so different from the kinds of cyclical disturbances that have occurred in the past – even during the great mass extinctions of prehistoric times – that we cannot expect ecological systems to recover to their previous states.[533]

For example, the scientific advisory committee that was appointed to advise the United States Forest Service about forest management recommended that ecological sustainability should be the foundation for forest management and that such sustainability should be achieved by ascertaining the historical range of variability of the ecological processes of a planning area, such as soil fertility, productivity, and biochemical cycles:

> Because ecosystems are dynamic and variable, the concept of the "historic range of variability" is used to characterize the variation and distribution of ecological conditions occurring in the past. This concept allows one to compare the ecological conditions that will be created under proposed management scenarios to past conditions. The more the prospective conditions differ from the conditions during recent millennia, the greater the expected risk to native species, their habitats, and the long-term stability of ecological processes.[534]

Excess disturbance may also significantly reduce an ecological system's productivity.[535] For example, where suppression of the normal forest fire cycle has caused heavy buildup of dead wood on

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532. David Tilman & Clarence Lehman, *Human-caused Environmental Change: Impacts on Plant Diversity and Evolution*, 98 PROC. NAT'L ACAD. SCI. USA 5433 (2001).

533. Michael L. Rosenzweig, *Loss of Speciation Rate Will Impoverish Future Diversity*, 98 PROC. NAT'L ACAD. SCI. USA 5404 (2001).

534. COMM. OF SCIENTISTS, U.S. DEP'T OF AGRIC., SUSTAINING THE PEOPLE'S LANDS: RECOMMENDATIONS FOR STEWARDSHIP OF THE NATIONAL FORESTS AND GRASSLANDS INTO THE NEXT CENTURY 147 (March 15, 1999). *See also* Ken Lertzman & Joseph Fall, *From Forest Stands to Landscapes: Spatial Scales and the Roles of Disturbances*, *in* ECOLOGICAL SCALE: THEORY AND APPLICATIONS 339, 366-67 (David L. Peterson & V. Thomas Parker eds., 1998). For a discussion of the committee report, see Charles F. Wilkinson, *A Case Study in the Intersection of Law and Science: The 1999 Report of the Committee of Scientists*, 42 ARIZ. L. REV. 307 (2000).

535. Productivity refers to the extent to which an ecological system can convert the sun's energy into matter and is measured by weighing the accumulated biomass and determining the amount of energy necessary to support that biomass. A DICTIONARY OF ECOLOGY, *supra* note 147, at 316-18. For a discussion of the origins of the productivity concept, see DONALD WORSTER, NATURE'S ECONOMY: A HISTORY OF ECOLOGICAL IDEAS 306-11 (2d ed. 1994).

the ground, a fire that eventually occurs may be so hot as to destroy soil bacteria that would have remained viable in a normal fire.[536] If a critical mass of resources is lost in the renewal process, the system may collapse. Thus, if a forest fire is followed by heavy rains before adequate revegetation, sufficient soil may be eroded such that the area will no longer support a forest.[537]

Ecologists believe that they will be able to identify parameters that bound the limits of many kinds of ecological systems to absorb such changes without collapsing.[538] The ability of a system to return to its normal dynamics after perturbation has been called its "homeorhetic stability";[539] where such stability exists, the system tends to return to its original "preperturbation *trajectory* or rate of change."[540] Holling thinks that many terrestrial ecological systems seem to keep most of their functions under stress even though species composition changes.[541]

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536. Virginia H. Dale et al., *Ecological Principles and Guidelines for Managing the Use of Land*, 10 ECOLOGICAL APPLICATIONS 639, 653 (2000). *See* Turner & Dale, *supra* note 342, at 760; Mark W. Schwartz & Sharon M. Hermann, *Midwestern Fire Management: Prescribing a Natural Process in an Unnatural Landscape, in* CONSERVATION IN HIGHLY FRAGMENTED LANDSCAPES 213, 222-24 (Mark W. Schwartz ed., 1997).

537. Robert T. Paine et al., *Compounded Perturbations Yield Ecological Surprises*, 1 ECOSYSTEMS 535 (1998) (collapse is often caused when different kinds of disturbance take place within a short time frame); Holly T. Dublin et al., *Elephants and Fire as Causes of Multiple Stable States in the Serengeti-Mara Woodlands*, 59 J. OF ANIMAL ECOLOGY 1147 (1990) (combination of fire and elephants convert forests to grassland); Hans W. Paerl et al., *Ecosystem Impacts of Three Sequential Hurricanes (Dennis, Floyd, and Irene) on the United States' Largest Lagoonal Estuary, Pamlico Sound, NC*, 98 PROC. NAT'L ACAD. SCI. USA 5655 (2001) (explaining that if the frequency of hurricanes increases due to climate change, it may cause long-term changes in coastal habitats).

538. Judy L. Meyer, *The Dance of Nature: New Concepts in Ecology*, 69 CHI.-KENT L. REV. 875, 882 (1994). Michael Huston has proposed a model for evaluating the impact of disturbance dynamics on biological diversity in which the key variables are frequency or intensity of disturbances on the vertical axis and rate of population growth and competitive displacement on the horizontal axis. Maximum diversity occurs when conditions are roughly equal on each scale. MICHAEL A. HUSTON, BIOLOGICAL DIVERSITY: THE COEXISTENCE OF SPECIES ON CHANGING LANDSCAPES 131-55 (1994). Experiments involving the gradual removal of single species and the measurement of the effect of the removal on the remaining system suggest that "systems have an appreciable buffering capacity to compensate for species loss but that there is a threshold of change that will overwhelm the damping effect of biodiversity, with an associated break point of ecosystem function to quite different levels." Ernst-Detlef Schulze & Harold A. Mooney, *Ecosystem Function of Biodiversity: A Summary, in* BIODIVERSITY AND ECOSYSTEM FUNCTION 497, 501 (1994).

539. Jianguo Wu & Orie L. Houcks, *From Balance of Nature to Hierarchical Patch Dynamics: A Paradigm Shift in Ecology*, 70 Q. REV. BIOLOGY 439, 444 (1995).

540. Christensen et al., *supra* note 134, at 675 (emphasis in original).

541. "One recent explanation for this resilience and robustness" is that a relative few processes set the rhythm of ecological system dynamics. The diversity of species can be traced to "the function of a small set of variables and the niches they provide . . . . Therefore, these structuring variables are where the priority should be placed in investing to protect or enhance diversity." C.S. Holling et al., *Biodiversity in the Functioning of Ecosystems: An Ecological Synthesis, in* BIODIVERSITY LOSS: ECONOMIC AND ECOLOGICAL ISSUES 44, 48, 70 (Charles Perrings et al. eds., 1995). *See also* Anthony W. King, *Considerations of Scale and*

The emphasis on the importance of post-disturbance reconstruction leads ecologists to search for key structuring variables[542] that control reorganization.[543] Because the recognition of the importance of disturbance is relatively recent, post-disturbance phenomena have not been studied with the kind of standard protocols that would make it easy to do comparative research.[544] For some ecological functions, threshold variables indicating how much disturbance can be sustained before the system loses predictability can probably be ascertained.[545] These parameters may involve factors such as biomass volume, relative energy flows to various food chains, and mineral micro-nutrient stocks.[546] The rate of change may prove to be a key factor.[547]

Hierarchy, in ECOLOGICAL INTEGRITY AND THE MANAGEMENT OF ECOSYSTEMS 19, 25-27 (Stephen Woodley et al. eds., 1993) (many ecosystems retain resilience despite change in individual components); John A. Bissonette, *Scale-Sensitive Ecological Properties: Historical Context, Current Meaning, in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 3, 24 (John A. Bissonette ed., 1997) (identification of structuring variables would provide predictive theory for ecosystem changes across scales).

542. Ecologists use techniques such as gradient analysis and boundary analysis to understand trajectories of ecological change and facilitate selection of effective measurable parameters for assessing changes in the state of terrestrial ecological systems. KRISTIINA A. VOGT ET AL., ECOSYSTEMS: BALANCING SCIENCE WITH MANAGEMENT 224-34 (1996). *See also* Steward T.A. Pickett & Kevin H. Rogers, *Patch Dynamics: The Transformation of Landscape Structure and Function, in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 101, 122 (John A. Bissonette ed., 1997) (integration of gradient analysis and patch perspective is needed); V.T. Parker & S.T.A. Pickett, *Restoration as an Ecosystem Process: Implications of the Modern Ecological Paradigm, in* RESTORATION ECOLOGY AND SUSTAINABLE DEVELOPMENT 17, 28 (Krystyna M. Urbanska et al. eds., 1997); Roy Haines-Young, *Landscape Pattern: Context and Process, in* ISSUES IN LANDSCAPE ECOLOGY 33, 34 (John A. Wiens & Michael R. Moss eds., 1999).

543. *See, e.g.*, Norman L. Christensen, Jr., *Managing for Heterogeneity and Complexity on Dynamic Landscapes, in* THE ECOLOGICAL BASIS OF CONSERVATION: HETEROGENEITY, ECOSYSTEMS, AND BIODIVERSITY 167 (Steward Pickett et al., eds., 1997); Virginia H. Dale et al., *Ecosystem Management in the Context of Large, Infrequent Disturbances*, 1 ECOSYSTEMS 546, 552-54 (1998).

544. Turner & Dale, *supra* note 342.

545. Charles Perrings, *Biodiversity Conservation as Insurance, in* THE ECONOMICS AND ECOLOGY OF BIODIVERSITY DECLINE: THE FORCES DRIVING GLOBAL CHANGE 69, 71-72 (Timothy M. Swanson ed., 1995).

546. Mick Common & Charles Perrings, *Towards an Ecological Economics of Sustainability*, 6 ECOLOGICAL ECONOMICS 7, 31 (1992).

547. Theoretical studies examining the effects of landscape spatial pattern, when that pattern changes over time, have generally found that the rate of change in landscape pattern is far more important than the spatial pattern itself in affecting population survival. Aspects of spatio-temporal pattern are, for disturbances, disturbance rate, disturbance size, and temporal correlation in disturbances, and for ephemeral patches, rate of patch formation and patch lifespan.

Susan Harrison & Lenore Fahrig, *Landscape Pattern and Population Conservation, in* MOSAIC LANDSCAPES AND ECOLOGICAL PROCESSES 293, 297 (Lennart Hansson et al. eds., 1995).

Similar searches for predictive processes are underway in regard to aquatic environments. Such environments sometimes appear to be unpredictable chaotic systems, but ecologists increasingly believe that the systems' cyclical variations are kept within limits set by system parameters and that the management goal should be to maintain the chaotic system within its normal range of variation by ensuring that the parameters of the system are not exceeded.[548] In fisheries, for example, these parameters are the ecological characteristics that determine growth, reproduction, migration, hierarchy, and predation.[549] These factors are not always appreciated by those with short-term interests in the catch.[550]

As ecologists have increasingly recognized the important role that disturbance plays in the ecological cycle, it has become apparent that human response to the reorganization that follows disturbance plays a crucial role in sustaining the long-term health of the ecological system.[551] Historically, however, our responses to disturbance of the environment have focused almost exclusively on the immediate human losses that accompany the disturbance, with much less attention being paid to the long range impact on the ecology, the eventual economic impact of which may be much greater.[552] We provide insurance so that people can rebuild in flood plains or after hurricanes or fires, but we have paid little attention to efforts to ensure that the natural environment can effectively renew itself and continue to provide the ecological values to which we are accustomed.[553]

548. Judy L. Meyer, *The Dance of Nature: New Concepts in Ecology*, 69 CHI.-KENT L. REV. 875, 882 (1994).

549. James A. Wilson et al., *Chaos, Complexity and Community Management of Fisheries*, 18 MARINE POLICY 291, 297-98 (1994) ("These aspects of a chaotic system can be learned. We can also learn when, what and how *not* to fish so that we do not disrupt the basic functioning of the system.").

550. A report by the National Research Council recommended that fishing regulators "recognize the importance of species interactions, conserve biodiversity, and permit utilization only when the ecosystem or its productive potential is not damaged." COMM. ON ECOSYSTEM MGMT. FOR SUSTAINABLE MARINE FISHERIES, NAT'L RESEARCH COUNCIL, SUSTAINING MARINE FISHERIES 113 (1999). For a readable account of some of the issues involved in applying ecological concepts to the oceans, see CARL SAFINA, SONG FOR THE BLUE OCEAN (1997).

551. Dale et al., *supra* note 543, at 551-53 ("The first step in managing recovery is to evaluate the site potential.").

552. Claudia Pahl-Wostl, *Ecosystem Organization Across a Continuum of Scales: A Comparative Analysis of Lakes and Rivers*, *in* ECOLOGICAL SCALE: THEORY AND APPLICATIONS 141, 147 (David L. Peterson & V. Thomas Parker eds., 1998) (human management of lakes and rivers may cause extreme floods to become more common).

553. DENNIS S. MILETI, DISASTERS BY DESIGN: A REASSESSMENT OF NATURAL HAZARDS IN THE UNITED STATES 31-33 (1999).

Some ecologists suggest that hierarchically organized ecological systems may have "natural integrators" that can serve as measures of ecological system integrity in a manner roughly analogous to the way that the body temperature of warm-blooded animals serves as an indicator of health.[554] For example, soil characteristics produced by geological forces have a major impact on ecological processes such as patterns of species diversity, endemism, and productivity.[555] Sometimes the integrator may be more indirect, such as when the foraging process of a wolf pack is a key factor affecting the "temporal and spatial variability of their prey."[556]

Although ecologists are still at an early stage in the process of trying to identify the indicators of resilience,[557] the availability of large-scale ecological research methodology makes the task seem less hopeless. Certainly our traditional methods of managing natural resources have failed to produce resilient ecological systems, and the need to pin down indicators of resilience should have high priority.[558] A panel of the National Research Council recently concluded: "[W]ithout quantitative theories, we have only limited ability to predict rates of change or specific losses and gains that will follow a perturbation in the environment . . . . [A] concerted effort during the coming decade could bring substantial advances."[559]

The first parts of this article explored some of the ideas that have been generated by research in ecology at large scales. Large-scale ecology tells us that competition rarely produces a survival of the fittest except in narrowly confined environments and that coexistence is the norm in variable environments. It suggests that our concern with habitat fragmentation ought to be limited to those habitats where extensive homogeneity is really needed to prevent extinction. It leads us to appreciate that disturbance, within historical limits, may be a necessary element of ecological processes. Furthermore, it leads us to hope that if we can keep human changes

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554. King, *supra* note 541, at 35-36; NAT'L RESEARCH COUNCIL, *supra* note 3, at 23-25 (2000).

555. Michael Huston, Dirt is Destiny: Common Constraints on Plants, Animals, and People (unpublished paper delivered at the Conference on Integration across Ecological Scales, Tex. A & M Univ., Feb. 25, 2000) (on file with author).

556. King, *supra* note 541, at 36.

557. *See* Daniel Simberloff, *Flagships, Umbrellas, and Keystones: Is Single-Species Management Passé in the Landscape Era?*, 83 BIOLOGICAL CONSERVATION 247, 254-55 (1998) (Identification of keystone species may lead to understanding of reorganization processes).

558. *See generally* Carl Folke et al., *Ecological Practices and Social Mechanisms for Building Resilience and Sustainability, in* LINKING SOCIAL AND ECOLOGICAL SYSTEMS: MANAGEMENT PRACTICES AND SOCIAL MECHANISMS FOR BUILDING RESILIENCE 414, 428-31 (Fikret Berkes & Carl Folke eds., 1998).

559. COMM. ON GRAND CHALLENGES IN ENVTL SCIENCES, NAT'L RESEARCH COUNCIL, GRAND CHALLENGES IN ENVIRONMENTAL SCIENCES 22 (2001) (citations omitted).

to the environment within historical parameters, we have hope of obtaining a metastability that will minimize the collapse of ecological systems. But it also suggests that unless we can bring under control the gradual alterations of the environment that produce unidirectional change, we may be creating risks beyond the ability of science to predict. The remainder of the article looks at policy implications of these ideas.

IV. PROPOSALS FOR LAWMAKERS

Today's legal scholarship increasingly recognizes that laws dealing with natural resources need to be reevaluated in light of current scientific knowledge on large-scale ecology.[560] My reading of the scientific literature on ecology has led me to make the following suggestions for policies and programs that lawmakers should consider. I have limited these suggestions to ideas derived from large-scale ecology, recognizing however that other types of ecological research also should be the basis for policy recommendations. Moreover, I have not included recommendations on the kind of additional research that the government should fund, although that is clearly an important issue.

A. *Use Better Ecological Data in Implementing Laws*

Although the technology for generating ecological data has improved greatly, the efforts to obtain and disseminate such data are far from ideal. The following suggestions are examples of ways in which such data could be made more broadly available so that it could be more effectively utilized in the implementation of a wide range of existing laws.

1. Facilitate Access to Large-Scale Ecological Information

Large-scale ecology requires the collection and analysis of enormous quantities of biological information. Modern satellites and computers make this possible, but it can be very expensive.[561]

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560. My colleague Dan Tarlock has been one of the leaders in this reevaluation. *See* A. Dan Tarlock, *The Nonequilibrium Paradigm in Ecology and the Partial Unraveling of Environmental Law*, 27 LOY. L.A. L. REV. 1121 (1994). *See also* A. Dan Tarlock, *Environmental Law: Ethics or Science?*, 7 DUKE ENVTL. L. & POL'Y F. 193 (1996). Eric Freyfogle has pointed out that Aldo Leopold was one of the early observers to recognize that human-induced changes caused damage, not because they disrupted a static balance of nature, but because they altered dynamic and flexible environments too violently and rapidly. Eric T. Freyfogle, A Sand County Almanac *at 50: Leopold in the New Century*, 30 ENVTL. L. REP. 10058, 10063-64 (2000). *See also* Doremus, *supra* note 485, at 33-35.

561. *See generally* S.A. DRURY, IMAGES OF THE EARTH: A GUIDE TO REMOTE SENSING (2d ed. 1998); Barry L. Johnson, *The Role of Adaptive Management as an Operational Approach for*

National governments should take the lead in making this data available for research.

i. Proceed to Implement a National Biological Survey

In September, 1993, Secretary of the Interior Bruce Babbitt proposed the creation of a new entity within the Department of the Interior to collect and analyze biological information. His goal, as his Solicitor John Leshy explained, was "to insulate research science from applied science in the Department by creating the National Biological Survey (NBS). Babbitt saw NBS, staffed with research scientists drawn from the Department's several bureaus, as the biology counterpart of the venerable U.S. Geological Survey, founded by the icon John Wesley Powell."[562] It was to be called the National Biological Survey to establish its status as a parallel to the older U.S. Geological Survey. [563] The idea of such an entity was not new; a division or bureau of biological survey had been in existence since 1896, until it was merged into the new Fish and Wildlife Service in 1939.[564]

Babbitt's proposal was supported by a report by the National Research Council endorsing the idea of an institution that would have the responsibility for "inventorying, mapping, and monitoring biotic resources; performing basic and applied research on species, groups of species, populations, and ecosystems; and providing the scientific support and technical assistance needed for management and policy decisions in DOI."[565] Secretary Babbitt created the NBS by executive order, and the NBS entered into cooperative agreements with various state agencies to obtain and monitor biological data.[566] These actions generated a good deal of optimism that funds would be made available for better biological data.[567] Unfortunately, the NBS proposal ran into what Joseph Sax has aptly characterized as the "ecologically backward-looking" Congress

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Resource Management Agencies, 3(2) CONSERVATION ECOLOGY 8 (1999), *available at* http://www.consecol.org/vol3/iss2/art8.

562. John D. Leshy, Essay, *The Babbitt Legacy at the Department of the Interior: A Preliminary View*, 31 ENVTL. L. 199, 206 (2001).

563. J.B. Ruhl, *Biodiversity Conservation and the Ever-expanding Web of Federal Laws Regulating Nonfederal Lands: Time for Something Completely Different?*, 66 U. COLO. L. REV. 555, 574 (1995).

564. The chronology of the biological survey is explained on the web page of the Biological Division of the United States Geological Survey, *at* http://biology.usgs.gov (last visited Jan. 12, 2002).

565. COMM. ON THE FORMATION OF THE NAT'L BIOLOGICAL SURVEY, NAT'L RESEARCH COUNCIL, A BIOLOGICAL SURVEY FOR THE NATION viii (1993).

566. Ruhl, *supra* note 563, at 574-75.

567. Robert B. Keiter, *Beyond the Boundary Line: Constructing a Law of Ecosystem Management*, 65 U. COLO. L. REV. 293, 323-33 (1994).

that was elected in November, 1994.[568] What remained at the end of Babbitt's tenure was a small unit within the United States Geological Survey that is currently doing important biological research, but its future is questionable, and its funding has never been adequate.[569]

The need for consolidation and analysis of biological data on a national and global basis is one of the top priorities of scientists seeking to cope with losses of biological diversity.[570] Congress should re-examine the sound conclusions of the 1993 National Research Council Report and institute a National Partnership for a Biological Survey in the form the Council recommended. It would provide a more efficient information base from which to make planning decisions and would create an "organized framework for collaboration among federal, regional, state, and local organizations, both public and private."[571]

ii. Make Ecological Data Readily Available

A great deal of long term ecological data was collected before modern systems of data storage and retrieval were available. There is a pressing need for funds to digitize this information and to publish it in usable form, complete with documentation about how the data was collected.[572] Current data also needs to be quickly accessible at reasonable cost. The scientific community has long held somewhat ambivalent feelings about the desire to obtain better data. Although each scientist would like to have access to as much data as possible, that same scientist may be quite reluctant to disclose data prior to its publication. This reflects both the competitive realities of the race to get credit in the academic community for being the first to publish and the danger that data released before being thoroughly tested and checked would be the source of potential embarrassment.[573]

568. Joseph L. Sax, Comment on John Harte's Paper, "*Land Use, Biodiversity, and Ecosystem Integrity: The Challenge of Preserving Earth's Life Support System*", 27 ECOLOGY L.Q. 1003, 1009 (2001).

569. Thomas E. Lovejoy, *The Quantification of Biodiversity: An Esoteric Quest or a Vital Component of Sustainable Development?, in* BIODIVERSITY: MEASUREMENT AND ESTIMATION 81, 82 (D.L. Hawksworth ed., 1995) (Most people labor under an "illusion that all that really matters is a handful of plant and animal species used as foods enlivened by a few more used as spices, with a couple of domestic animals such as dogs or cats thrown in for amusement.").

570. Robert M. May, *Conceptual Aspects of the Quantification of the Extent of Biological Diversity, in* BIODIVERSITY: MEASUREMENT AND ESTIMATION 13, 18-19 (D. L. Hawksworth ed., 1995).

571. NAT'L RESEARCH COUNCIL, *supra* note 565, at 54.

572. *See generally* Ad Hoc Committee of the Ecological Soc'y of Am., Report of the Committee on the Future of Long-term Ecological Data (1995).

573. Robert L. Fischman & Vicky J. Meretsky, *Endangered Species Information: Access and*

Some businesses will pay significant sums for ecological data, but much ecological research is done by nonprofit institutions. It is important to keep in mind that charging for data may make it difficult to acquire such data for those who are not involved in converting land to economic benefit.[574] The National Research Council has noted that although new information technology has generally provided expanded access to government data, "in some parts of the government, the evolution of the information infrastructure has instead been associated with a trend toward the commercialization of government information, increasingly limiting the amounts of information that can be accessed inexpensively by the public."[575]

Under the Freedom of Information Act (FOIA),[576] federal government agencies and any other entities receiving federal funding must disclose scientific data only if it has been relied on as the basis for a government decision or if it has served as the basis of a formal scientific publication.[577] Robert Fischman and Vicky Meretsky have pointed out that the delay between the collection of ecological data and its publication may lead to poor decision making in fields such as conservation biology that require immediate decisions based on the best data available.[578]

The National Research Council recommends that "[a]s a general principle, the basic data created or collected by the federal government should be available at a modest cost, usually not to exceed the direct costs associated with distribution of the data."[579] This is an important recommendation and should be implemented. In addition, many ecological data systems could probably be treated as "open source" technology that could be built on freely by

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Control, 41 WASHBURN L. J. 90, 111-13 (2001) (suggesting that scientists be required to provide annual reports on long term studies that affect critical species).

574. For a discussion of the history of efforts to regulate the cost of remote sensing data, see Charles Davies et al., *Moving Pictures: How Satellites, the Internet, and International Environmental Law Can Help Promote Sustainable Development*, 28 STETSON L. REV. 1091, 1139-41 (1999). *See also* Jeremy Speich, Comment, *The Legal Implications of Geographical Information Systems (GIS)*, 11 ALB. L.J. SCI. & TECH. 359, 378-80 (2001) (cost of GIS data remains a problem).

575. COMM. ON INTELLECTUAL PROPERTY RIGHTS AND THE EMERGING INFORMATION INFRASTRUCTURE, NAT'L RESEARCH COUNCIL, THE DIGITAL DILEMMA: INTELLECTUAL PROPERTY IN THE INFORMATION AGE (2000); Executive Summary *reprinted in* 62 OHIO ST. L.J. 951, 959-60 (2001).

576. 5 U.S.C. § 552 (2000).

577. OMB Circular A-110, 64 Fed. Reg. 54,926, 54,927-30 (Oct. 8, 1999).

578. Fischman & Meretsky, *supra* note 573.

579. NAT'L RESEARCH COUNCIL, *supra* note 575, at 960.

scientists throughout the world.[580] This would facilitate further advances in ecological data collection and processing.

2. Develop Performance Standards for Alteration of Ecological Processes

The more science learns about ecological processes, the more difficult it has been to pin down precise criteria for deciding whether changes in the processes are good or bad. In an environment where ecological conditions are undergoing constant change, how do you decide whether a particular change is both abnormal and undesirable?[581] United States government scientists have been simultaneously developing two approaches: (1) procedures to evaluate risks to ecological functions,[582] and (2) establishment of indicators that can measure future changes in ecological systems.[583]

i. Use Ecological Risk Assessment Procedures

The Scientific Advisory Board (SAB) of the United States Environmental Protection Agency (EPA) has been wrestling with the problem of adjusting the agency's planning to modern concepts of ecological science.[584] In 1998, the EPA published guidelines for ecological risk assessment based on the SAB's work.[585] The guidelines illustrate the difficulty of defining adverse ecological effects.

The new ecological risk assessment procedures are phrased in bureaucratic jargon, but the basic outlines of the process can be easily understood. The first phase of the process, called "problem formulation," generates and evaluates preliminary ideas about "why ecological effects have occurred, or may occur, from human activities."[586] The second phase of the process, the analysis phase,

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580. On the open source approach, see Shawn W. Potter, *Opening Up to Open Source*, 6 RICH. J.L. & TECH. 24 (2000).

581. "Communities and ecosystems are in constant flux, even without human interference," so how do we define a "normal state, and how do we separate, except in the most obvious cases, the effects of human and natural disturbances?" DAVID EHRENFELD, BEGINNING AGAIN: PEOPLE AND NATURE IN THE NEW MILLENNIUM 141 (1993).

582. *See* notes *infra* 584-97.

583. *See* notes *infra* 598-611. For a perspective on ecological impact assessment under the European Union rules, see JO TREWEEK, ECOLOGICAL IMPACT ASSESSMENT (1999).

584. See THE REPORT OF THE RESEARCH STRATEGIES COMM., U.S. EPA, FUTURE RISK: RESEARCH STRATEGIES FOR THE 1990S (1988).

585. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. 26,845 (May 14, 1998). For an external review draft of a supplemental EPA publication, see *Planning for Ecological Risk Assessment: Developing Management Objectives*, *at* http://www.epa.gov/ncea/raf/dmo.htm (June 2001).

586. The first phase of the process should result in agreement on the identification of: (1)

examines the relationship of the stressors and targets in more detail. The result is called a "stressor-response profile."[587] The third phase is the preparation of a risk characterization report containing (1) quantified or qualitative estimates of the extent of the risk created by various stressors; (2) recommended management and research tasks aimed at reducing and better understanding the risk; and (3) a monitoring program to provide continuing evaluation and revision of the management activities.[588]

The most interesting part of the guidelines is the discussion of how one decides whether a stressor's impact is adverse.[589] The guidelines offer the following criteria for "evaluating adverse changes" in assessment endpoints: (1) "[n]ature of effects and intensity of effects"; (2) "[s]patial and temporal scale"; and (3) "[p]otential for recovery."[590] They recognize that "[n]atural ecosystem variation can make it very difficult to observe (detect) stressor-related perturbations," given such things as natural fluctuations in populations of species and cyclic events such as migrations and tides which may "mask or delay stressor-related effects."[591]

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targets (or endpoints, as they are called in the Guidelines), which are ecological objectives that can be measured (e.g., nesting success of target species, presence of certain pollutants in water, etc.); (2) a conceptual model that describes the processes by which it is assumed that "stressors" may be affecting the ecological objectives; and (3) an analysis plan to evaluate risk hypotheses to determine how they will be assessed. Selection of measurable endpoints should concentrate on those factors that "help sustain the natural structure, function, and biodiversity of an ecosystem" and that are sensitive to change caused by stressors. Conceptual models for ecological risk assessment are to be developed "from information about stressors, potential exposure, and predicted effects on an ecological entity (the assessment endpoint)." Uncertainty can be reduced by developing alternative models which will be revisited and revised if necessary during the assessment process. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,851-64.

587. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,873. This includes figuring out how the adverse impact takes place (called "exposure analysis" by the EPA), and using an "ecological response analysis" to evaluate (1) "how the magnitude of the effects change with varying stressor levels," (2) whether the evidence shows "that the stressor causes the effect," and (3) whether there is a link between the effects and the assessment endpoint. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,873.

588. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,882.

589. After the changes in the endpoints have been estimated, "[t]he next step is to interpret whether these changes are considered adverse. Adverse ecological effects, in this context, represent changes that are undesirable because they alter valued structural or functional attributes of the ecological entities under consideration. The risk assessor evaluates the degree of adversity, which is often a difficult task and is frequently based on the risk assessor's professional judgment." Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,890.

590. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,890.

591. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,890. The guidelines go on to point out that fluctuations may seem more or less important depending on how large an area is surveyed and how long a time frame is considered. Guidelines for Ecological Risk Assessment, 63 Fed. Reg at 26,891.

The guidelines define recovery as "the rate and extent of return of a population or community to some aspect of its condition prior to a stressor's introduction .... Because ecosystems are dynamic and, even under natural conditions, constantly changing in response to changes in the physical environment (e.g., weather, natural disturbances) or other factors, it is unrealistic to expect that a system will remain static at some level or return to exactly the same state that it was before it was disturbed."[592] The extent to which changes are reversible, the existence of a natural disturbance pattern, and the likely rate of recovery should be considered.[593]

When the final guidelines are compared with the proposed guidelines published in 1996,[594] one can see that the authors became increasingly troubled with the issue of how to determine whether a change is adverse. This led to a concern that better ecological indicators were needed to provide baselines against which the magnitude and direction of change could be ascertained.[595] The highly technical language of the guidelines[596] also reinforced the need to provide indicators that communicated information that the public could easily understand.[597] Apparently in response to these concerns, the EPA asked the National Research Council to undertake a study of potential "ecological indicators."[598] The Council's report was published in 2000.[599]

ii. Adopt Ecological Indicators

The scientists who wrote the Council's report looked with obvious envy at the precision and neutrality that have long been

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592. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,891 (citation omitted).

593. Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,891.

594. Proposed Guidelines for Ecological Risk Assessment, 61 Fed. Reg. 47,552 (Sept. 9, 1996). For comments on the earlier draft, see Lisa Heinzerling, *Reductionist Regulatory Reform*, 8 FORDHAM ENVTL. L.J. 459, 466-72 (1997).

595. U.S. EPA, EVALUATION GUIDELINES FOR ECOLOGICAL INDICATORS (Laura Jackson et al. eds., 2000).

596. For a comment on the guidelines, see United States Army Legal Services Agency, *Environmental Law Division Notes,* 1999 ARMY LAW. 38, 39-41 (1999).

597. Andrew Schiller et al., Communicating Ecological Indicators to Decision Makers and the Public, 5 CONSERVATION ECOLOGY (1) 19 (2001), *available at* www.consecol.org/vol5/iss1/art19.

598. The National Research Council is the research arm of the National Academy of Sciences and the National Academy of Engineering.

599. NAT'L RESEARCH COUNCIL, *supra* note 3. For another version of ecological indicators, see Mark A. Harwell et al., *A Framework for an Ecosystem Integrity Report Card*, 49 BIOSCIENCE 543 (1999). *See also* INTEGRATING ECONOMIC AND ECOLOGICAL INDICATORS: PRACTICAL METHODS FOR ENVIRONMENTAL POLICY ANALYSIS (J. Walter Milon & Jason F. Shogren eds., 1995).

attributed to some of the national economic indicators.[600] They explicitly defined their search criteria to focus on indicators that would quantify and "simplify information about complex phenomena to improve communication."[601] Quite naturally, the Council interpreted its charge as both scientific and educational.

Like the EPA, the Council recognized the difficulty of identifying "normal" baselines against which to compare the current status of any indicator. Not only are many ecosystems and habitats poorly understood, but most ecosystems are characterized by large-scale fluctuations in which the abundance of species may change dramatically, seasonally and from year to year.[602] "Therefore, baselines must specify typical patterns of variation and incorporate ways of deciding whether a particular fluctuation or trend falls outside the bounds of 'normal' variation. The greater the normal variability in an ecosystem, the more difficult it is to identify abnormal variation."[603] The report also recognizes that it will be crucial to define the spatiotemporal scale at which an indicator is used.[604]

The report recommends specific indicators for which national data should be generated and published: (1) "Land Cover and Land Use," (2) "Total Species Diversity," (3) "Native Species Diversity," (4) "Nutrient Runoff," (5) "Soil Organic Matter," (6) "Productivity, including Carbon Storage, Net Primary Production (NPP), and Production Capacity," (7) "Lake Trophic Status," (8) "Stream Oxygen," and (9) "Nutrient-Use Efficiency and Nutrient Balance."[605] The Council says that although these indicators are "well grounded in theory and supported by extensive data, further research . . . might also suggest new indicators that are better than or that can be added to the set of indicators then in use."[606]

Although other studies of potential ecological indicators are also underway,[607] lawmakers should begin to implement the Council's

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600. NAT'L RESEARCH COUNCIL, *supra* note 3, at 19 ("Thousands of people pay close attention to changes in the gross domestic product").

601. *Id.* at 27. The report also acknowledges that "[e]cological indicators must be developed and used with the knowledge that substantial uncertainty will always exist." *Id.* at 26.

602. *See, e.g.*, J. E. Hewitt et al., *Assessing Environmental Impacts: Effects of Spatial and Temporal Variability at Likely Impact Scales*, 11 ECOLOGICAL APPLICATIONS 1502 (2001) (noting difficulty of assessing impact under conditions of spatial and temporal variability). *See generally* IAN F. SPELLERBERG, MONITORING ECOLOGICAL CHANGE (1991).

603. NAT'L RESEARCH COUNCIL, *supra* note 3, at 24.

604. *Id.* at 54.

605. *Id.* at 66. The search for indicators is also taking place at an international level. *See* Virginia H. Dale, *Criteria and Indicators for Assessing Sustainability of Forest Management: Conservation of Biodiversity*, 78 BULL. ECOLOGICAL SOC'Y OF AM. 291 (1997) (report of workshop on tropical forest indicators).

606. NAT'L RESEARCH COUNCIL, *supra* note 3, at 17.

607. The Heinz Center expects to publish a series of proposed indicators in 2002. The

recommendations by creating an administrative process for setting and maintaining indicators that will define the parameters of "normal" ecological change. There is no more important objective if we are to be able to distinguish between metastability of ecological systems and ecological collapse.[608] In addition, the United States government should cooperate with other countries and international institutions in systematic monitoring of worldwide ecological conditions.[609] The success of the International Panel on Climate Change is a model for cooperation among scientists worldwide that should be replicated in ecology.

3. Require Large-Scale Environmental Impact Analyses

One of the most contentious issues in environmental impact analysis under the National Environmental Policy Act[610] has been the extent to which the agency should take a broad look at impacts on large space and time scales.[611] Ecologists urge the making of land use decisions in a regional context.[612] Agencies, however, being usually short on funds and under pressure from constituents who are eager to see construction begin, typically like to reduce the scope of impact analysis to the extent possible. This reduction in scope has given rise to frequent litigation challenging the absence of analysis of cumulative and indirect impacts[613] and the failure to produce programmatic impact statements.[614]

Heinz Ctr., *The State of the Nation's Ecosystems* (Summer 2001), *available at* http://www.heinzctr.org/Programs/Reporting/overview.htm (last visited May 29, 2002). *See* Robin O'Malley & Kate Wing, *Forging a New Tool for Ecosystem Reporting*, 42 ENV'T (3) 20 (2000). *See also* Robert V. O'Neill et al., *Monitoring Environmental Quality at the Landscape Scale*, 47 BIOSCIENCE 513 (1997) (recommending use of remote sensing to monitor environmental quality).

608. Gretchen C. Daily, *Developing a Scientific Basis for Managing Earth's Life Support Systems*, 3 CONSERVATION ECOLOGY (2):14 (Oct. 27, 1999), *available at* http://www.consecol.org/vol3/iss2/art14 (scientists must establish "standard metrics and systematic monitoring of the magnitude and rates of change in human impacts on ecosystems").

609. Edward Ayensu et al., *International Ecosystem Assessment*, 286 SCI. 685 (Oct. 22, 1999) (urging creation of global ecosystem assessment).

610. 42 U.S.C. § 4331 (1994).

611. WILLIAM H. RODGERS, JR., ENVIRONMENTAL LAW 947-57 (2d Hornbook ed., 1994). For an interesting discussion of the role of geographic scale in environmental law, see Daniel A. Farber, *Stretching the Margins: The Geographic Nexus in Environmental Law*, 48 STAN. L. REV. 1247 (1996).

612. Dale et al., *supra* note 536, at 656.

613. RODGERS, JR., *supra* note 611, at 947-52.

614. Jon C. Cooper, *Broad Programmatic Policy and Planning Assessments under the National Environmental Policy Act and Similar Devices: A Quiet Revolution in an Approach to Environmental Considerations*, 11 PACE ENVTL. L. REV. 89, 123-36 (1993). *See* RODGERS, JR., *supra* note 611 at 936-41.

A classic example is found in a 2001 district court decision finding inadequate a group of environmental impact statements (EIS's) relating to the Sonoran pronghorn.[615] This antelope-like animal was once common in the Sonoran desert region, but it now is reduced to a few hundred individuals that occupy federal lands in Southern Arizona.[616] The lands it occupies are managed by a number of separate federal agencies: an Air Force bombing range, a national monument, a wildlife refuge, and lands leased for grazing by the Bureau of Land Management; thirteen federal agencies are involved in the management of these lands.[617]

Each of the federal agencies prepared its own EIS for the activities it was conducting or permitting on this complex of federal lands. The agencies were required to follow the regulations adopted by the Council on Environmental Quality, which require that, in explaining the environmental consequences of proposed actions under NEPA, an EIS discuss "the relationship between short-term uses of man's environment and the maintenance and enhancement of long-term productivity, . . . any irreversible or irretrievable commitments of resources which would be involved in the proposal should it be implemented,"[618] and the indirect[619] and cumulative effects[620] of the proposed action.

It was the cumulative effects issue that tripped up the federal agencies in Arizona. The Defenders of Wildlife argued that the various military activities on the Southern Arizona lands, together with activities of the border patrol, recreational users, and grazing lessees, adversely impacted the Pronghorn and that the EIS's prepared by the various federal agencies were inadequate because each EIS focused only on the activities of a single agency.[621] The court agreed, pointing out that the "Pronghorn move across this relatively discreet area of land entirely under federal management without regard to which federal agency is responsible for

615. Defenders of Wildlife v. Babbitt, 130 F. Supp. 2d 121, 138-39 (D.C. Cir. 2001).

616. A NATURAL HISTORY OF THE SONORAN DESERT 487-90 (Steven J. Phillips & Patricia Wentworth Comus eds., 2000). The Sonoran pronghorn is a subspecies of the pronghorn, which is considered to be rare throughout its range in the Western United States. It is the sole surviving member of its taxonomic family and considered to be an evolutionarily isolated animal. Bruce A. Stein et al., *A Remarkable Array: Species Diversity in the United States*, *in* PRECIOUS HERITAGE: THE STATUS OF BIODIVERSITY IN THE UNITED STATES 55, 71 (Bruce A. Stein et al. eds., 2000).

617. *Defenders of Wildlife*, 130 F. Supp. 2d at 122-23.

618. Council on Environmental Quality Environmental Impact Statement, 40 CFR § 1502.16 (2001). This language comes directly from the statute itself. 42 U.S.C. § 4332 (C) (iv) and (v) (1994).

619. Council on Environmental Quality Terminology, 40 CFR § 1508.8 (b) (2001).

620. Council on Environmental Quality Terminology, 40 CFR § 1508.7 (2001).

621. *Defenders of Wildlife*, 130 F. Supp. 2d at 123-24.

administering a particular area."[622] It sent the matter back to the agencies with directions to coordinate their environmental analyses.[623]

In the light of decisions like these,[624] the need for cumulative impact analyses has begun to attract the attention of federal agency attorneys.[625] The EPA has also issued guidance on the application of environmental assessments to ecological processes,[626] which should make it easier for agencies to address cumulative ecological issues.[627] But it will take a distinct change of mind set to persuade most agencies to look at the issues from a larger perspective. The Council on Environmental Quality should amend its regulations to ensure that agencies cooperate in the preparation of environmental assessments on larger time and space scales. Alternatively, Congress should amend NEPA to prevent the agencies from fragmenting the environmental assessment into meaninglessness.[628]

4. Analyze the Environmental Impact of Inaction

The first generation of environmental laws, which still form the foundation of our environmental legislation, incorporated many features of static ecological thinking. Congress sought environmental stability: lakes and rivers were to be zoned for permanent uses; air quality was expected to reach specific and unchanging criteria; and the centerpiece of these environmental

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622. *Id.* at 129. The court also found that the biological opinions written under the ESA were inadequate for similar reasons. *Id.* at 125-31.

623. *Id.* at 138. For a discussion of the case, see William Snape III et al., *Protecting Ecosystems Under the Endangered Species Act: The Sonoran Desert Example*, 41 WASHBURN L.J. 14, 27-28 (2001).

624. For additional cases, see Natural Res. Def. Council v. Hodel, 865 F.2d 288 (D.C. Cir. 1988); Fritiofson v. Alexander, 772 F.2d 1225, 1243-46 (5th Cir. 1985); Muckleshoot Indian Tribe v. United States Forest Serv., 177 F.3d 800, 810-12 (9th Cir. 1999); Carmel-by-the-Sea v. United States Dep't of Transp., 123 F.3d 1142, 1151 (9th Cir. 1997); Nat'l Audubon Soc'y v. Butler, 160 F. Supp. 2d 1180 (W.D. Wash. 2001); Kettle Range Conservation Group v. United States Forest Serv., 148 F. Supp. 2d 1107 (E.D. Wash. 2001); Friends of the Earth v. United States Army Corps of Eng'rs, 109 F. Supp. 2d 30 (D.C. Cir. 2000); Defenders of Wildlife v. Ballard, 73 F. Supp. 2d 1094 (D. Ariz. 1999); Am. Lands Alliance v. Kenops, Civil No. 99-80-KI, 1999 U.S. Dist. LEXIS 13910 (D. Or. Aug. 30, 1999).

625. United States Army Legal Services Agency, *Environmental Law Division Notes: NEPA and Cumulative Impact Analysis*, 2001 ARMY LAW. 33, 35 (2001).

626. OFFICE OF FEDERAL ACTIVITIES, EPA, CONSIDERING ECOLOGICAL PROCESSES IN ENVIRONMENTAL IMPACT ASSESSMENTS (1999).

627. Robert L. Fischman, *The EPA's NEPA Duties and Ecosystem Services*, 20 STAN. ENVTL. L.J. 497 (2001) (advocating more quantification of ecological benefits in environmental assessment).

628. On the rather remote chances of Congress taking on the task of amending NEPA, see Paul S. Weiland, *Amending the National Environmental Policy Act: Federal Environmental Protection in the Twenty-first Century*, 12 J. LAND USE & ENVTL. LAW 275 (1997).

laws, the National Environmental Policy Act (NEPA),[629] sought to weigh prospective human activities against a "no action" alternative.[630]

Despite its non-substantive character, NEPA has continued to provide the framework for environmental impact analysis that dominates environmental planning. Court interpretations of NEPA have used federal action–not inaction–as the trigger, and the regulations have assumed that the least impact on the environment was the best. In other words, NEPA effectively created a presumption that doing nothing was the ideal alternative.[631] As one court put it, an environmental impact statement is not required "in order to leave nature alone."[632]

The assumption that inaction is desirable is so pervasive that only recently has it been questioned.[633] For example, EPA's guidelines for ecological risk assessment[634] fall into the pattern of assuming that any change is undesirable. Although EPA says that its ecological risk assessment process could be adapted to predict beneficial changes in ecological systems,[635] the guidelines as presently drafted make no provision for balancing beneficial ecological changes against adverse changes.[636]

But inaction can have an adverse impact on the ecology of an area just as surely as action can. A classic example is the San Bruno Mountain controversy that led to the 1982 amendments to

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629. 42 U.S.C. §4321 (2001). "NEPA was the first piece of federal legislation to raise ecology to primary status . . . . It rested on the premise that ecology could provide the rationale to guide administrative action." A. Dan Tarlock, *Biodiversity Federalism*, 54 MD. L. REV. 1315, 1326 (1995).

630. Council on Environmental Quality Environmental Impact Statement, 40 C.F.R. § 1502.14 (d) (2001).

631. *See* Note, *Does NEPA Require an Impact Statement on Inaction*, 81 MICH. L. REV. 1337, 1360 (1983).

632. Nat'l Ass'n of Property Owners v. United States, 499 F. Supp. 1223, 1265 (D. Minn. 1980), *aff'd*, Minnesota v. Block, 660 F.2d 1240 (8th Cir. 1981). For discussion of other cases involving the distinction between action and inaction, see Michelle Formy Duval, Recent Development, *Eighth Circuit Finds Decision to Discontinue Herbicide Use in National Forest Does Not Require an Environmental Impact Statement*, 4 S.C. ENVTL. L.J. 74 (1995); C.A. Gavilondo, Recent Development, Sabine River Auth. v. Dept. of Interior: *NEPA's Applicability to Federal Inaction*, 67 TUL. L. REV. 560 (1992).

633. "At best, ecosystems can be managed rather than restored or preserved, and management will become a series of calculated, risky experiments." Tarlock, *supra* note 629, at 1330. I have offered some ideas about adaptive management of natural resources in Fred Bosselman, *Adaptive Management and Intergenerational Equity*, 12 U. FLA. J.L. & PUB. POL'Y 311, 320-28 (2001).

634. *See* discussion *supra* notes 584-97.

635. "Although intended to evaluate adverse effects, the ecological risk assessment process can be adapted to predict beneficial changes or risk from natural events." Guidelines for Ecological Risk Assessment, 63 Fed. Reg. 26,846, 26,848 (May 14, 1998).

636. *See, e.g.*, Guidelines for Ecological Risk Assessment, 63 Fed. Reg. at 26,891 (discussing "recovery").

the ESA authorizing Habitat Conservation Plans. San Bruno Mountain is just south of San Francisco, within the boundaries of three different municipalities having varying attitudes toward development. Private land on the mountain is the home of an endangered butterfly. The habitat is deteriorating because of the invasion of exotic species and use by trespassers in off-road vehicles. The area is one of high environmental consciousness–Stanford and Berkeley are nearby.[637]

Developers and local environmental groups brought agencies together, formed a committee, and prepared a habitat plan. Its key features were that developers would build housing on 14% of critical habitat area and would donate over 80% of the habitat area to the county. The developers agreed to contribute $60,000 per year to the county for management, to be funded by impact fees and assessments. This fund was to be used to remove exotic vegetation and to fence and patrol the area to keep out intruders. The USFWS approved a permit based on the plan, then used the plan as the basis for an amendment to the statute, which the court subsequently used as support for upholding the permit in a suit brought by a dissident Berkeley group.[638]

The most significant feature of the plan was the active management component to keep out invading species and ATVs so that the net result of development was to enhance survival of species. At that time, the ESA did not force or even encourage private landowners to take affirmative actions that would help an endangered species.[639] Had the area simply been left alone, biologists believed that a rare butterfly occupying the area would have soon become extinct.[640] The habitat conservation planning process that grew out of this case[641] has recognized that positive management of the environment is often essential for the protection of rare species.[642]

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637. For a recent survey and history of the area, see Rasa Gustaitus, *Secrets of San Bruno Mountain*, 17 CA. COAST & OCEAN 7 (Spring 2001).

638. Friends of Endangered Species, Inc. v. Jantzen, 760 F.2d 976, 982-83 (9th Cir. 1985).

639. Barton H. Thompson, Jr., *People or Prairie Chickens: The Uncertain Search for Optimal Biodiversity*, 51 STAN. L. REV. 1127, 1156-61 (1999) (§ 9 of ESA offers no incentive for improvement of habitat).

640. For a more complete description of the San Bruno Mountain plan on which the amendments were based, see Lindell L. Marsh and Robert D. Thornton, *San Bruno Mountain Habitat Conservation Plan*, *in* MANAGING LAND USE CONFLICTS: CASE STUDIES IN SPECIAL AREA MANAGEMENT 114 (David J. Brower & Daniel S. Carol eds., 1987).

641. This type of interjurisdictional planning was a prototype of many similar efforts ongoing in what Joseph Sax has called the "new age" of environmental restoration. Joseph L. Sax, *The New Age of Environmental Restoration*, 41 WASHBURN L.J. 1, 1 (2001).

642. *See, e.g.*, Loggerhead Turtle v. County Council of Volusia County, 120 F. Supp. 2d 1005, 1015 (M.D. Fla. 2000).

University of California at Davis law professor Holly Doremus points out that "ecologists tell us that most areas dedicated to the preservation of nature cannot simply be left to their own devices, but will require active human management."[643] There are many parts of the United States in which active intervention is essential if ecological systems are to be protected.[644] Hawaii is a huge, sad case study of the need for positive actions to combat ecological collapse. The Hawaiian Islands are over 2000 miles from any continent or other islands of substantial size.[645] The islands grew from volcanoes rising out of the ocean,[646] so plants and animals had to reach the islands after traversing huge expanses of open water. As a result, many groups of plants and animals, including reptiles and conifers, for example, were never able to reach the islands in pre-human times.[647] The relatively small number of species that succeeded in reaching the islands found ways of adapting to the wide range of niches that evolved as the volcanic activity subsided and the environment became more hospitable.[648] Through "adaptive radiation," the original immigrants evolved into a wide range of plants and animals uniquely adapted to ecological systems specific to Hawaii.[649]

With the arrival of the Polynesians, who were the first human settlers in Hawaii, came pigs, dogs, chickens, rats, and lizards. Captain Cook and other sea captains brought cattle, goats, sheep, and horses. The mongoose was later introduced, as were more than 130 species of birds.[650] In addition, non-native plants were brought into the islands in great numbers. There were some 900 species of plants at the time Captain Cook landed. Since that time, another 870 non-native species of plants have become established and are reproducing in the wild.[651] Many of these species are highly

643. Doremus, *supra* note 485, at 57.

644. The Everglades is a classic example. *Id.* at 61. In other countries, as well, such intervention is needed. *See* Z. Naveh, *Mediterranean Uplands as Anthropogenic Perturbation-dependent Systems and Their Dynamic Conservation Management, in* TERRESTRIAL AND AQUATIC ECOSYSTEMS: PERTURBATION AND RECOVERY 544, 548-50 (Oscar Ravera ed., 1991) (Complete cessation of human interference in nature reserves in the Mediterranean region has caused biological impoverishment).

645. SHERWIN CARLQUIST, HAWAII: A NATURAL HISTORY 81 (1970).

646. Christina Heliker, *The Volcanic Origin of the Hawaiian Islands, in* CONSERVATION BIOLOGY IN HAWAI'I 11, 11 (Charles P. Stone & Danielle B. Stone eds., 1989).

647. CARLQUIST, *supra* note 645, at 82.

648. ROBERT J. WHITTAKER, ISLAND BIOGEOGRAPHY: ECOLOGY, EVOLUTION, AND CONSERVATION 93-104 (1998).

649. CARLQUIST, *supra* note 645, at 122-38; Bruce A. Stein et al., *supra* note 616, at 89-92.

650. Charles P. Stone, *Non-Native Land Vertebrates, in* CONSERVATION BIOLOGY IN HAWAI'I 88, 88-91 (Charles P. Stone & Danielle B. Stone eds., 1989).

651. Clifford W. Smith, *Non-Native Plants, in* CONSERVATION BIOLOGY IN HAWAI'I 60, 60 (Charles P. Stone & Danielle B. Stone eds., 1989).

invasive, such as the Banana poka, lantana, and blackberry, and are crowding out native vegetation.[652]

Today, many of the native plants and animals of Hawaii have become extinct or are gravely threatened; for example, at least 77 endemic species of birds have become extinct since the arrival of the Polynesians.[653] The most serious issue facing native ecological systems in Hawaii is not action but inaction.[654] Removal of invasive exotic species of plants and animals is a constant and difficult undertaking[655] for which appropriations have been difficult to find.[656]

Is it feasible to apply the National Environmental Policy Act to inaction as well as action? In the absence of specific CEQ regulations, it is impossible to imagine judicial support for such an interpretation, given the obvious hostility of the current Supreme Court to the statute.[657] And the difficulties of creating a justiciable issue over whether inaction is the equivalent of action are considerable.[658]

But NEPA does contain general language authorizing federal agencies to undertake environmental assessments that go beyond the mandatory submission of EIS's for major federal actions required by section 102(2)(C).[659] It requires each agency to "identify and develop methods and procedures, in consultation with the Council on Environmental Quality, . . . which will insure that

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652. *Id.* at 63-65. For an overall review of the current status of Hawaii's ecology, see Lloyd L. Loope, *Hawaii and the Pacific Islands, in* UNITED STATES GEOLOGICAL SURVEY, STATUS AND TRENDS OF THE NATION'S BIOLOGICAL RESOURCES, *at* http://biology.usgs.gov/s+t/SNT/index.htm (last visited December 4, 2001).

653. COMM. ON SCIENTIFIC ISSUES IN THE ENDANGERED SPECIES ACT, NAT'L RESEARCH COUNCIL, SCIENCE AND THE ENDANGERED SPECIES ACT 31-32 (1995). Other estimates range from about 60 to over 100 species of birds lost in Hawaii. WHITTAKER, *supra* note 648, at 236.

654. Leonard A. Freed, *Extinction and Endangerment of Hawaiian Honeycreepers: A Comparative Approach, in* GENETICS AND THE EXTINCTION OF SPECIES 137, 151-55 (Laura F. Landweber & Andrew P. Dobson eds., 1999). For a comment criticizing the recent decision of the Ninth Circuit Court of Appeals in Nat'l Parks & Conservation Ass'n v. United States Dept. of Transp., 222 F.3d 677 (9th Cir. 2000) for failing to require a large scale examination of the problem of alien species invasion in Hawaii, see Comment, *NEPA and the Danger of Alien Species Introduction*, 42 JURIMETRICS 31 (2001).

655. For a description of the process of removing pigs from natural areas, see Kenneth Brower, *The Pig War, in* A WORLD BETWEEN THE WAVES 71 (Frank Stewart ed., 1992).

656. Faith Campbell, *The Appropriations History, in* BALANCING ON THE BRINK OF EXTINCTION 134, 139-43 (Kathryn A. Kohm ed., 1991).

657. RODGERS, JR., *supra* note 611, at 838-39.

658. The generality of NEPA's language makes it difficult to enforce it judicially in the absence of implementing regulations. Oliver A. Houck, *Is That All?: A Review of The National Environmental Policy Act: An Agenda for the Future, by Lynton Keith Caldwell*, 11 DUKE ENVTL. L. & POL'Y F. 173, 178-81 (2000) (book review).

659. 42 U.S.C. § 4332 (C) (1994); *see* Dinah Bear, *The Promise of NEPA, in* BIODIVERSITY AND THE LAW 178, 182-83 (William J. Snape ed., 1996).

presently unquantified environmental amenities and values may be given appropriate consideration in decision making along with economic and technical considerations."[660] Many people, including the primary author of NEPA, have criticized the failure to use the statute to achieve more substantive environmental goals.[661]

The Council on Environmental Quality could and should adopt regulations encouraging some form of environmental assessment, although not necessarily the EIS required for major federal actions,[662] for those ecological problems that are suffering from inaction. Ecological science tells us that inaction in the face of impending ecological collapse is as fatal as any action. The difficulty of defining inaction should not be an excuse for failing to give it a try.

B. Focus on Post-Disturbance Reorganization

Governments need to think in advance about how they are going to react to the kinds of ecological disturbance that are likely to occur. They need to (1) think about what kind of disturbances are likely and how they will react to them; (2) manage the disturbance when it occurs, and (3) aid the reorganization process.[663] In some cases, it may be necessary to avoid the temptation to try to control the reorganization process too closely; often, the ecological systems will reorganize themselves effectively with little assistance.[664]

One business executive has said that managers need to plan like a fire department. The department "can't predict where the next fire will be, so it has to shape . . . [a] team that is capable of responding to the unanticipated,"[665] which often may require reversing earlier decisions.[666] The one area where the federal

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660. 42 U.S.C. § 4332 (B) (1994).

661. *See generally* LYNTON KEITH CALDWELL, THE NATIONAL ENVIRONMENTAL POLICY ACT: AN AGENDA FOR THE FUTURE (1998).

662. For suggestions on ways to limit inaction EIS's, see Note, *Does NEPA Require an Impact Statement on Inaction*, 81 MICH. L. REV. 1337, 1361-67 (1983).

663. Dale et al., *supra* note 543, at 550.

664. *Id.* at 551-52. *See, e.g.*, W.H. Van der Putten et al., *Plant Species Diversity as a Driver of Early Succession in Abandoned Fields: A Multi-site Approach*, 124 OECOLOGIA 91, 98 (2000) (querying whether sowing seeds of plants that usually occupy land at later stages of succession will speed up the succession process).

665. WILLIAM E. FULMER, SHAPING THE ADAPTIVE ORGANIZATION: LANDSCAPES, LEARNING, AND LEADERSHIP IN VOLATILE TIMES 139 (2000) (quoting Andy Grove).

666. James C. Scott, in his study of the failure of many international development programs, advocates a planning process that (1) takes small steps, (2) favors reversibility, (3) plans on surprises, (4) and assumes that future planners will be inventive. JAMES C. SCOTT, SEEING LIKE A STATE: HOW CERTAIN SCHEMES TO IMPROVE THE HUMAN CONDITION HAVE FAILED 345 (1998).

government appears to be succeeding in this effort is where it is, in fact, acting like a fire department.

1. Fire Policy

One result of large scale ecological research is a new attitude towards forest fires. A certain degree of forest fire activity is now seen as the kind of perturbation needed to preserve many forest systems.[667] For example, fires contribute to biodiversity by providing opportunities for the establishment and maintenance of early successional species.[668] But excessive fire can result in the permanent collapse of forest ecosystems.[669] When viewed on the spatial and temporal scale of an individual stand of forest to be harvested, any fire looks like a cataclysmic disturbance that should be eliminated.[670] But viewed on a spatial scale appropriate to the frequency of recurrence, fire can be seen as necessary to allow reorganization of the system.[671] For example, fire can often prevent the rapid transitions caused by invasive species.[672]

Traditional ecology thought of forests, like other ecological systems, as growing through cycles leading to "maturity."[673] In the early stages, the forest would be occupied by fast growing species that would subsequently be replaced by the longer lasting dominant

667. R.V. O'NEILL ET AL., A HIERARCHICAL CONCEPT OF ECOSYSTEMS 167-69 (1986). *See* Norman L. Christensen, *Shrubland Fire Regimes and Their Evolutionary Consequences, in* THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS 85 (S.T.A. Pickett & P.S. White eds., 1985) (in old stands the net aboveground biomass accumulation approaches zero). Management of fire regimes has been complicated by their complex, chaotic nature, which limits the predictability of natural events and suggests the need for affirmative fire management. Christensen, Jr., *supra* note 543, at 179. Complexity is further increased when fire is compounded with other disturbances. Robert T. Paine et al., *Compounded Perturbations Yield Ecological Surprises*, 1 ECOSYSTEMS 535, 542 (1998). For an interesting analysis of the potential impact of fire management on climate change, see David Tilman et al., *Fire Suppression and Ecosystem Carbon Storage*, 81 ECOLOGY 2680 (2000).

668. John D. Stuart, *Effects of Fire Suppression on Ecosystems and Diversity, in* UNITED STATES GEOLOGICAL SURVEY, STATUS AND TRENDS OF THE NATION'S BIOLOGICAL RESOURCES (1999), *available at* http://biology.usgs.gov/s+t/SNT/noframe/lu107.htm (last visited Dec. 4, 2001).

669. For example, fire is being used in Southeast Asia as a land clearing mechanism, and the smoke has had a serious impact on air quality over long distances. Nicholas A. Robinson, *Forest Fires as a Common International Concern: Precedents for the Progressive Development of International Environmental Law*, 18 PACE ENVTL. L. REV. 459, 474-77 (2001).

670. The history of public attitudes toward fire is chronicled in STEPHEN J. PYNE, FIRE IN AMERICA (2d ed. 1997).

671. R.V. O'NEILL ET AL., A HIERARCHICAL CONCEPT OF ECOSYSTEMS 86 (1986). *See, e.g.*, Turner & Dale, *supra* note 342.

672. Mark W. Schwartz & Sharon M. Hermann, *Midwestern Fire Management: Prescribing a Natural Process in an Unnatural Landscape, in* CONSERVATION IN HIGHLY FRAGMENTED LANDSCAPES 213, 214-15 (Mark W. Schwartz ed., 1997).

673. *See, e.g.*, MARION CLAWSON, AMERICA'S LAND AND ITS USES 130-31 (1972).

species characteristic of the mature forest.[674] Today, ecologists typically view natural forests as intricate combinations of patches of different habitats of differing ages–the differences resulting from disturbances such as fire, disease, storms, etc.[675]

The ability to study forests over long time periods has led ecologists to view any ecological system that appears to be moving toward maturity as one that is becoming "overconnected" into an artificial manifestation of stability.[676] Thus forests that meet Clements' ideal of the climax may be most susceptible to fire and disease because at that stage, an ecological system is "an accident waiting to happen."[677] For example, the most easily accessible parts of the immense forests of Siberia have been clear-cut without any attempt at regeneration, but the great bulk of the forests are untouched and over-mature with many dead standing trees. Such forests are highly susceptible to fire, pests, and disease. In both clearcut and over-mature forests, the risk of a collapse and a flip to a new ecological system is great.[678]

Unlike most of the newer ecological ideas, the theory that disturbance can be beneficial has caught the public's attention ever

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674. Peter S. White & Jonathan Harrod, *Disturbance and Diversity in a Landscape Context*, *in* WILDLIFE AND LANDSCAPE ECOLOGY: EFFECTS OF PATTERN AND SCALE 128, 145-49 (John A. Bissonette ed., 1997).

675. NOSS & COOPERRIDER, *supra* note 194, at 183-86 (old growth forests are rich in species because of both vertical and horizontal heterogeneity). *See also* LEVIN, *supra* note 91, at 112 ("[L]ocal variability and heterogeneity provide the material for change;" disturbance and renewal maintain the diversity).

676. Charles D. Canham & P.L. Marks, *The Response of Woody Plants to Disturbance: Patterns of Establishment and Growth*, *in* THE ECOLOGY OF NATURAL DISTURBANCE AND PATCH DYNAMICS 197, 214 (S.T.A. Pickett & P.S. White eds., 1985) (even climax species depend on disturbances to complete their life cycle). If fire recurs frequently and regularly, it may no longer be appropriate to consider it a disturbance at all. Continued modification of the environment in response to fire leaves it with those species that resist fire or return quickly after fire; thus fire "has become incorporated into the system as a normal, working component . . . . The new system has evolved to an emergent, higher level of organization." AHL & ALLEN, *supra* note 124, at 170.

677. C.S. Holling, *Biodiversity in the Functioning of Ecosystems: An Ecological Synthesis*, *in* BIODIVERSITY LOSS: ECONOMIC AND ECOLOGICAL ISSUES 44, 65 (Charles Perrings et al. eds.,1995). *See, e.g.*, DAVID M. RIZZO & PATRICIA E. MALONEY, TAHOE RESEARCH GROUP, CAUSES AND PATTERNS OF TREE MORTALITY IN LAKE TAHOE BASIN FORESTS, *available at* http://trg.ucdavis.edu/research/annualreport/contents/forest/ article24.html (last visited May 29, 2002).

678. Sten Nilsson & Anatoly Shvidenko, Is Sustainable Development of the Russian Forest Sector Possible?, IUFRO Occasional Paper #11, ISSN 1024-414X. *See also* Ken Lertzman & Joseph Fall, *From Forest Stands to Landscapes: Spatial Scales and the Roles of Disturbances*, *in* ECOLOGICAL SCALE: THEORY AND APPLICATIONS 339, 354 (David L. Peterson & V. Thomas Parker eds., 1998) (explaining that unlike natural disturbance, clearcutting removes the complex post-disturbance structural diversity that is typical of patchy wildfires). *But see* F. Siegert et al., *Increased Damage From Fires in Logged Forests During Droughts Caused by El Niño*, 414 NATURE 437 (2001) (finding that selectively-cut forests in Borneo are most susceptible to destruction by fire during drought).

since the 1988 fires that swept in and around Yellowstone Park.[679] The severity of the fires was blamed on the National Park Service policy of extinguishing smaller fires and not clearing underbrush.[680] But by 2000, regrowth was well underway,[681] and the fires could be looked back upon as "just another chapter in a book whose pages keep turning."[682] Today, ecologists carefully analyze the relative benefits of forest restoration and prescribed burning on various types of habitat in the park.[683] The idea that fire is simply an ordinary part of the normal life cycle of forests and grasslands has become widely accepted.[684]

Seen at the scale of an individual forest or grassland fire, the chaotic behavior of fire regimes limits our ability to predict the behavior of any specific fire.[685] But on larger space and time scales, it is clear that natural fire regimes have played an important role in the development and maintenance of ecological systems.[686] Ecologists believe that an understanding of these fire regimes will help reestablish ecological processes after fires.[687] While paleoecology cannot yet give us detailed pictures of prehistoric fire patterns, we need to try to understand and simulate such conditions to the extent possible, given all of the other human resources that are impacted by fire.[688]

Government policy increasingly recognizes the need for fires, although the implementation of this policy near urban areas has

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679. A readable report of the fires and the condition of the burned areas a decade later is in MARY ANN FRANKE, YELLOWSTONE IN THE AFTERGLOW: LESSONS FROM THE FIRES (2000). The history of the ecological impact of fires caused by humans is summarized in Stephen J. Pyne, *Forged in Fire: History, Land, and Anthropogenic Fire*, *in* ADVANCES IN HISTORICAL ECOLOGY 42 (William Balée ed., 1998).

680. *See* MICHAEL FROME, REGREENING THE NATIONAL PARKS 169-71 (1992). A more careful analysis of the effects of National Park Service fire policy is found in Robert B. Keiter, *Preserving Nature in the National Parks: Law, Policy, and Science in a Dynamic Environment*, 74 DENV. U. L. REV. 649, 664-89 (1997).

681. Anthony D. Barnosky et al., *Temperate Terrestrial Vertebrate Faunas in North and South America: Interplay of Ecology, Evolution, and Geography with Biodiversity*, 15 CONSERVATION BIOLOGY 658, 668-69 (2001) (stating that Yellowstone sees replenishment by pre-existing and new species after each disturbance).

682. FRANKE, *supra* note 679, at 3.

683. *See, e.g.*, A. J. Hansen et al., *Spatial Patterns of Primary Productivity in the Greater Yellowstone Ecosystem*, 15 LANDSCAPE ECOLOGY 505, 519-20 (2000) (suggesting need to restore low-elevation cottonwood-aspen-fir forests in Yellowstone).

684. NOSS & COOPERRIDER, *supra* note 194, at 186-88 (1994) (noting that the species in any forest have adapted to a certain disturbance regime and that they are likely to be adversely affected by any alteration in that regime).

685. Christensen, Jr., *supra* note 543, at 179.

686. Schwartz & Hermann, *supra* note 536, at 213.

687. Virginia H. Dale et al., *Ecosystem Management in the Context of Large, Infrequent Disturbances*, 1 ECOSYSTEMS 546, 550 (1998).

688. Schwartz & Hermann, *supra* note 536 at 223.

been difficult.[689] The extensive fires in the Western United States in the year 2000 posed a real test for fire managers. The Interior and Agriculture Departments issued a report analyzing the response to these fires.[690] The report noted that the earlier policy of aggressive fire suppression appeared to be successful back in the 1970s, but it set the stage for today's intense fires:

> Species of trees that ordinarily would have been eliminated from forests by periodic, low-intensity fires began to become a dominant part of the forest canopy. Over time, these trees became susceptible to insects and disease. Standing dead and dying trees in conjunction with other brush and downed material began to fill the forest floor. The resulting accumulation of these materials, when dried by extended periods of drought, created the fuels that promote the type of wildfires that we have seen this year . . . .[691]
>
> In short, decades of aggressive fire suppression have drastically changed the look and fire behavior of Western forests and rangelands. Forests a century ago were less dense and had larger, more fire-resistant trees. For example, in northern Arizona, some lower elevation stands of ponderosa pine that once held 50 trees per acre, now contain 200 or more trees per acre. In addition, the composition of our forests have changed from more fire-resistant tree species to non-fire resistant species such as grand fir, Douglas-fir, and subalpine fir. As a result, studies show that today's wildfires typically burn hotter, faster, and higher than those of the past.[692]

689. John D. Leshy, *The Babbitt Legacy at the Department of the Interior: A Preliminary View*, 31 ENVTL. L. 199, 205-206 (2001).

690. Protecting People and Sustaining Resources in Fire-Adapted Ecosystems--A Cohesive Strategy; Notice, 65 Fed. Reg. 67,479, 67,481 (Nov. 9, 2000).

691. SECRETARIES OF AGRIC. AND INTERIOR, MANAGING THE IMPACT OF WILDFIRES ON COMMUNITIES AND THE ENVIRONMENT: A REPORT TO THE PRESIDENT IN RESPONSE TO THE WILDFIRES OF 2000 (2000), *available at* http://clinton4.nara.gov/CEQ/firereport.html (last visited Sept. 27, 2001).

692. *Id.* The report also noted that because new development is occurring in fire-prone areas, often adjacent to Federal land, "firefighters today often spend a great deal more time and effort protecting structures than in earlier years. Consequently, firefighting has become more complicated, expensive, and dangerous." *Id.*

The federal agencies have recognized the important function that fire plays in forests and grasslands. They have responded to the buildup of fuels in forests and rangelands through a variety of approaches, including controlled burns,[693] the physical removal of undergrowth and other unnatural concentrations of fuel, and the prevention and eradication of invasive plants.[694] The report noted that the flammability of undergrowth has been augmented by invasive species such as cheatgrass, which is now common in the West. After a fire, "it grows earlier, quicker, and higher than native grasses. Then it dies, dries, and becomes fuel."[695]

The agencies emphasized that the program to reduce undergrowth was not an excuse to increase commercial logging:

> The removal of large, merchantable trees from forests does not reduce fire risk and may, in fact, increase such risk. Fire ecologists note that large trees are "insurance for the future — they are critical to ecosystem resilience." Targeting smaller trees and leaving both large trees and snags standing addresses the core of the fuels problem.[696]

Following the issuance of the report, the Forest Service published a notice indicating that it planned to adopt a cohesive strategy for fire management and forest health programs.[697] The full text of the report was attached to the notice. The report relied heavily on large-scale ecological science in its conclusions.[698]

The report staunchly defends the application of large-scale ecological knowledge to the practical world of fire management. This is a major breakthrough in the promotion of adaptive management in the federal government. It remains to be seen whether a new administration will continue this emphasis on science.[699]

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693. The use of controlled burns goes back at least to 1975. *See* Paul F. Boucher & Ronald D. Moody, *The Historical Role of Fire and Ecosystem Management of Fires: Gila National Forest, New Mexico*, 20 TALL TIMBERS FIRE ECOLOGY CONFERENCE PROCEEDINGS 374 (1998).

694. SECRETARIES OF AGRIC. AND INTERIOR, *supra* note 691.

695. *Id.*

696. *Id.*

697. Protecting People and Sustaining Resources in Fire-Adapted Ecosystems–A Cohesive Strategy; Notice, 65 Fed. Reg. 67,480 (Nov. 9, 2000).

698. SECRETARIES OF AGRIC. AND INTERIOR, *supra* note 691.

699. Joe Grossman, *Blue Planet: Fire Plan Work Gets Mixed Reviews*, UPI SCIENCE NEWS, Sept. 12, 2001.

2. Remediation of Environmental Damage

Another area in which the management of natural resources needs to incorporate large-scale ecology is in the implementation of statutes dealing with cleanup of environmental damage caused by such things as hazardous waste and oil spills.[700] One of the more difficult issues in these processes has been the way in which the managers of the site should deal with the natural resources that were destroyed. Although the regulations impose significant obligations on polluters, some of the regulations' objectives seem to be based on outmoded ideas about ecological systems.

Congress required those who caused oil or hazardous waste pollution to pay the governmental agencies that manage natural resources for the damage such resources incur but left to the administrators the problem of drafting regulations defining such damage. In response to attempts during the Reagan administration to minimize the expense associated with non-economic issues, rules were proposed that gave minimal weight to resources that lacked significant economic value.[701] A strong backlash against these rules resulted in new rules that required restoration of the natural resources on each site. In 1997, the D.C. Circuit upheld most of the regulations implementing the natural resource damages sections of the Oil Pollution Act of 1990.[702] The regulations set restoration cost as the basic standard for measuring damages.[703] Although the earlier rules were ridiculously inadequate, and although damage to natural resources ought to result in stiff penalties,[704] the idea that restoration is the desirable approach may be inconsistent with today's awareness that ecological systems are continually changing.

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700. The primary examples are the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), Pub. L. No. 96-510, 94 Stat. 2767 (1980) (codified as amended at various places in 42 U.S.C.) and the Oil Pollution Act of 1990, 33 U.S.C. §§ 2701-61 (2000).

701. Ohio v. United States Dept. of the Interior, 880 F.2d 432, 438 (D.C. Cir. 1989). *See* James L. Nicoll, *The Irrationality of Economic Rationality in the Restoration of Natural Resources*, 42 ARIZ. L. REV. 463, 465-68 (2000) (regulations which allowed for damages to be set at the lesser of restoration costs or lost economic value were contrary to Congressional intent that "intended restoration to be the 'basic measure of recovery'").

702. Gen. Elec. Co. v. United States Dept. Of Commerce, 128 F.3d 767, 779 (D.C. Cir. 1997) (upholding damages based on restoration costs).

703. *See also* Kennecott Utah Copper Corp. v. United States Dept. of the Interior, 88 F.3d 1191 (D.C. Cir. 1996) (upholding similar regulations under CERCLA). *See* Dale B. Thompson, *Valuing the Environment: Courts' Struggles with Natural Resource Damages*, 32 ENVTL. L. 57, 84-87 (2002).

704. James Peck, Comment, *Measuring Justice for Nature: Issues in Evaluating and Litigating Natural Resources Damages*, 14 J. LAND USE & ENVTL. L. 275 (1999). For a comparative study of the approaches of different national legal systems to the issue of natural resource damages, see EDWARD H. P. BRANS, LIABILITY FOR DAMAGE TO PUBLIC NATURAL RESOURCES (2001).

This is particularly true in those areas in which the climate is changing rapidly, such as the Arctic.[705]

The Alaskan oil spill caused by the Exxon Valdez in 1989 offers a good example.[706] Although media attention focused on attempts to save individual creatures, ecologists recognized that saving habitat was the important objective.[707] As a result of the extended litigation that followed the accident,[708] damages paid by Exxon in the amount of $120 million have been put into a fund, the income from which is to pay for a "Gulf Ecosystem Monitoring Program," a long term monitoring and research program for the northern Gulf of Alaska.[709]

Nearly $700 million of Exxon's settlement with the state and federal governments has been used to purchase over half a million acres of land to preserve as parks and wildlife refuges.[710] However, the panel of scientists set up to monitor the Gulf Ecosystem

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705. WORKING GROUP 1, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, THIRD ASSESSMENT REPORT: SUMMARY FOR POLICYMAKERS 13 (2000).

706. The Exxon Valdez spill was clearly the catalyst for the Oil Pollution Act of 1990, which passed the Senate without a single dissenting vote, even though attempts to strengthen oil spill laws had foundered for years until then.:

> In an approximate way, the Exxon Valdez accident was the product of a combination of failures that included erratic navigation by an incapacitated captain in a vulnerable vessel under poorly planned conditions. In a long (ninety-one pages), comprehensive (amendments were made to nine different statutes), and detailed response, Congress spread solutions across this spectrum of navigation, operations, vessel condition, and planning. Behind the Oil Pollution Act of 1990 are a wide variety of human behavioral assumptions about bad-weather observations, upstart second-officers, clever programmers, casual use of the auto-pilot, aggressive engineers, and careful planners. But it is the specter of the drunken captain, personified as Joseph Hazelwood, that drove this legislative engine.

William H. Rodgers, Jr., *Where Environmental Law and Biology Meet: Of Pandas' Thumbs, Statutory Sleepers, and Effective Law*, 65 U. COLO. L. REV. 25, 66-67(1993) (footnote omitted). *See also* Deborah S. Bardwick, *The American Tort System's Response to Environmental Disaster: The Exxon Valdez Oil Spill as a Case Study*, 19 STAN. ENVTL. L.J. 259 (2000).

707. A volunteer who organized citizens to hand-scrub the oil off hundreds of otters and birds now looks back on this effort: "Exxon spent $80,000 per otter that survived the cleaning, but at least half of those are thought to have died soon after they were released. So it was closer to $160,000 per animal. I think that money would have been better spent restoring and protecting habitat." *Sea of Crude, Legacy of Hope*, SIERRA 81 (Mar./Apr. 1999). An interesting book by a person who worked on the cleanup process is JEFF WHEELWRIGHT, DEGREES OF DISASTER: PRINCE WILLIAM SOUND: HOW NATURE REELS AND REBOUNDS (1994).

708. Bardwick, *supra* note 706, at 262; Robert E. Jenkins & Jill Watry Kastner, Comment, *Running Aground in a Sea of Complex Litigation: A Case Comment on the Exxon Valdez Litigation*, 18 UCLA J. ENVTL. L. & POL'Y 151 (1999/2000)..

709. *Exxon Valdez* OIL SPILL TRUSTEE COUNCIL, GULF ECOSYSTEM MONITORING: GEM SCIENCE PROGRAM NRC REVIEW DRAFT 4, April 21, 2000.

710. FRED BOSSELMAN ET AL., ENERGY, ECONOMICS AND THE ENVIRONMENT 428 (2000). *See* Diane S. Calendine, Comment, *Investigating the* Exxon Valdez *Restoration Effort: Is Resource Acquisition Really Restoration?*, 9 DICK. J. ENVTL. L. & POL'Y 341 (2000).

Monitoring Program believe that it has shown little progress, that it is "moving toward a piece-meal, small-scale, project-driven approach," and that it "seems to be losing sight of its ecosystem focus as it selects individual species for attention."[711]

Could the habitats affected by the Exxon Valdez spill ever be returned to their original condition, given the volume of oil spilled and the area covered?[712] And given the rapidity of climate change in Alaska,[713] would it have been possible to recreate an environment that was created by different climate conditions? The World Wildlife Fund predicts that as much as 70% of the natural habitat of the Arctic could be lost by the end of the century.[714] Given these conditions, restoration makes sense only if we construe the term loosely.[715]

Lawmakers need to recognize the insights of large-scale ecology in implementing restoration of ecological systems.[716] Rather than simply succumbing to a nostalgia for what once existed, they need to try to create functioning ecological systems that will actually work in present conditions and that will support ecological processes equivalent to what was destroyed.[717] This requires an analysis of how ecological systems reorganize themselves in

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711. COMMITTEE TO REVIEW THE GULF OF ALASKA ECOSYSTEM MONITORING PROGRAM, NAT'L RESEARCH COUNCIL, INTERIM REPORT 28 (Feb. 2001). *See, e.g.*, Thomas A. Dean & Stephen C. Jewett, *Habitat-specific Recovery of Shallow Subtidal Communities Following the* Exxon Valdez *Oil Spill*, 11 ECOLOGICAL APPLICATIONS 1456, 1468 (2001) (stating that rocky shores recovered relatively quickly but soft sediment habitats remain impacted).

712. For an examination of recovery from two major oil spills in Europe, see Y. Le Moal et al., *Perturbation and Recovery After the Two Major Oil Spills (*Amoco Cadiz *and* Tanio*), in* TERRESTRIAL AND AQUATIC ECOSYSTEMS: PERTURBATION AND RECOVERY 417 (Oscar Ravera ed., 1991).

713. *See generally* NAT'L ASSESSMENT SYNTHESIS TEAM, U.S. GLOBAL CHANGE RESEARCH PROGRAM, CLIMATE CHANGE IMPACTS ON THE UNITED STATES 283-312 (2001) (noting that extensive warming is predicted in Alaska).

714. Sarah Lyall, *A Global Warming Report Predicts Doom for Many Species*, N.Y. TIMES, Sept. 1, 2000, at A3. Public awareness of the warming of the Arctic was increased by reports that the ice has melted at the North Pole. Public attention was focused on the warming of the Arctic in the summer of 2000 when a scientific research team reported that there was open water, rather than ice, at the North Pole for the first time. John Noble Wilford, *Ages-Old Icecap at North Pole Is Now Liquid, Scientists Find*, N.Y. TIMES, Aug. 19, 2000, at A1.

715. Daniel Luecke of Environmental Defense says that ecosystem restoration should mean "The re-establishment of a balance in ecosystem structure and function to meet the needs of plants, animals, and human communities." Daniel F. Luecke, *An Environmental Perspective on Large Ecosystem Restoration Processes and the Role of the Market, Litigation, and Regulation*, 42 ARIZ. L. REV. 395, 396 (2000).

716. MUTSONORI TOKESHI, SPECIES COEXISTENCE: ECOLOGICAL AND EVOLUTIONARY PERSPECTIVES 274 (1999) (Except for fire, there has been little study in detail of the "characteristics and modes of operation of various forms of disturbance in a particular community on different spatio-temporal scales").

717. Alyson C. Flournoy, *Restoration Rx: An Evaluation and Prescription*, 42 ARIZ. L. REV.187, 195-96 (2000).

reaction to disturbance, so that such reorganization can be assisted and ecological collapse avoided. The regulations implementing the appropriate statutes should be examined to ensure that they reflect the current ideas of large-scale ecology.

C. *Counteract Unidirectional Environmental Change*

One corollary of the older Clementsian ecological theory was the idea that if we humans just stopped doing whatever "unnatural" things we were doing to an area it would eventually evolve back into its ideal climate condition. In other words, almost all human mistakes could be rectified by terminating them.[718] Needless to say, this has not proven to be the case, at least within time scales that we humans have experienced.[719] Large-scale ecology has shown us that many changes in the natural world are cyclical and that if we can keep these changes within normal parameters, the ecological systems should be resilient to these changes. But some of the changes humans are causing seem to be beyond the boundaries of any cycles that have occurred in the past.[720] Are these changes reversible?

1. Reversal

One such change is the increase of carbon dioxide in the air. Since accurate measurements of the amount of airborne carbon dioxide have begun, it has increased inexorably at the rate of 0.5% per year.[721] The overwhelming majority of serious scientists believe that the increase in emission of carbon dioxide and other greenhouse gases has contributed to the warming of the climate that has been taking place and that will continue at increasing rates throughout most regions of the United States.[722] Yet we are hesitant to expend resources on the reduction of greenhouse gas

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718. Furthermore, the emphasis put on stability, unique equilibria, and normative states [by the equilibrium theory] has historically promoted a view of a "benign Nature" able to cope with any sort of anthropogenic interference and manipulation, because trials (and errors) of any kind can be made with the assurance that recovery is always possible . . . .

De Leo & Levin, *supra* note 116.

719. Driving between the Allentown airport and my summer home in the Poconos, I pass through a valley that was the location of a Nineteenth-Century copper smelter. The barren landscape has experienced only minimal recovery a century later. For a description of the area, see BILL BRYSON, A WALK IN THE WOODS: REDISCOVERING AMERICA ON THE APPALACHIAN TRAIL 185-89 (1998).

720. *See* discussion *supra* notes 447-91.

721. GALE E. CHRISTIANSON, GREENHOUSE: THE 200-YEAR STORY OF GLOBAL WARMING 167 (1999).

722. COMM. ON THE SCIENCE OF CLIMATE CHANGE, NAT'L RESEARCH COUNCIL, CLIMATE CHANGE SCIENCE: AN ANALYSIS OF SOME KEY QUESTIONS 2 (2001).

emissions[723] because the lifestyle changes that would result from a program that would actually reverse the trend of carbon dioxide emissions[724] are staggering to contemplate.[725]

Similarly, despite our efforts to control water pollution in various ways, we seem to be steadily increasing the quantity of nutrients in coastal waters. A recent study suggests that the trend of increasing nitrate delivery by the Mississippi River to the Gulf of Mexico could be reduced by a 12% reduction of nitrogen fertilizer use in the river basin,[726] but the political inability to obtain cooperation from the sources of nonpoint source pollution makes it difficult to foresee an end to the steady growth of hypoxia in Gulf coastal waters, with its unforeseeable impact on the marine environment.[727]

The increase of carbon dioxide in the air and nitrogen in the water have not been dramatic, but they have been slow and steady.[728] The problems they create will increase year by year, burdening our descendants more with each generation, unless we

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723. *See generally* Symposium, *Innovations in Environmental Policy: The Psychology of Global Climate Change*, 2000 U. ILL. L. REV. 299 (2000).

724. James Hansen and some of his colleagues at NASA's Goddard Institute for Space Studies have published a paper that has attracted a great deal of attention: James Hansen et al., *Global Warming in the Twenty-First Century: An Alternative Scenario*, 97 PROC. NAT'L ACAD. SCI. U. S. 9875 (Aug. 29, 2000). They argue that trends in the emission of greenhouse gases other than carbon dioxide may be easier to control. They say that emissions of methane, the second biggest contributor to warming, may be easier and cheaper to reduce because efficient technology is available to reduce methane emissions significantly in regard to all of the major sources: rice cultivation, cattle raising, landfills, sewage treatment, pipeline leakage, and biomass burning. They also suggest that we can relatively easily reduce black carbon emissions from diesel fuel and coal, which have the effect of reducing cloud cover and thereby increasing warming. However, even if greater attention is paid to these new technologies the likelihood of short term reversal of greenhouse gas emission trends seems slight. *Id.*

725. For example, David Fleming, the director of the Lean Economy Initiative, a British environmental group, has proposed a system of "Domestic Tradable Quotas" that would allow the industrial economy to reinvent itself with a completely new way of meeting its energy needs. Every person would be given a Domestic Tradable Quota (DTQ), which would be an "equal per capita entitlement of 'carbon units' to cover domestic needs for fuel for all purposes, including private transport," and people could trade their units in the market. Over time, the total quantity of carbon units made available would be gradually reduced. Carbon units "would be surrendered–as 'virtual' ration coupons–to cover the purchase of all types of fuel and domestic energy." The greater the carbon emissions of the fuel or energy source, the more carbon units would have to be surrendered. "The whole transaction and all the calculations needed would be carried out using technology which is already commonplace for credit cards and direct debit systems." David Fleming, *Your Climate Needs You*, 67 TOWN & COUNTRY PLANNING 302 (Oct. 1998).

726. Gregory F. McIsaac et al., *Nitrate Flux in the Mississippi River*, 414 NATURE 166 (Nov. 8, 2001).

727. *See* discussion *supra* notes 492-512.

728. Most ecologists today would no longer support the idea that gradual change is always superior to rapid change because it provides more opportunity for adaptation, a view that was once popular. *See, e.g.*, RENÉ DUBOS, A GOD WITHIN 194-95 (1972).

can reverse the trends.[729] I am troubled by an assumption that my descendants will be able to solve ecological problems for which there is no historical precedent.[730] And as Holly Doremus has emphasized, the idea of ethical obligations to future generations resonates with a great many people, even including those without children of their own.[731] Programs to slow down these processes of unidirectional change have received some support at the national and international level,[732] and technological developments may provide new ways of coping with these issues efficiently,[733] but we would be kidding ourselves if we thought such programs or developments would avoid the need for both mitigation and adaptation to unidirectional change.[734]

2. Mitigation

Mitigation is the process by which the economic forces that drive environmental change are utilized to produce tradeoffs that

729. Why are we investing so little in solving long-range problems? Some people argue that our growing reliance on the stock market as the barometer of value is a major factor. The market encourages us to concentrate on quarterly results rather than long term prospects. Any corporate manager who proposes to sacrifice immediate gains for long-term investment runs the risk of being replaced or taken over. Consequently, managers "sometimes engage in activities counter-productive to the long-term interests of the company in order to 'meet their numbers.'" IRA C. MAGAZINER & ROBERT B. REICH, MINDING AMERICA'S BUSINESS: THE DECLINE AND RISE OF THE AMERICAN ECONOMY 193 (1982). Day trading and brokerage hype have added to this problem, as the long term investors who used to dominate the market have been joined by individual investors concerned primarily with short term swings in stock prices, and traditional pension plans that sought long-term securities are being replaced by plans that give employees the option of playing the market. *Everyone's Headache: Companies Wake Up to the Risks of Equity and Defined Benefit Schemes*, 361 THE ECONOMIST 8251 (Dec. 15, 2001).

730. *See* Bosselman, *supra* note 633, at 333.

731. Doremus, *supra* note 485, at 71-73.

732. The Kyoto Protocol, which is the international community's proposed answer to climate change, is insightfully analyzed in Lakshman Guruswamy, *Climate Change: The Next Dimension*, 15 J. LAND USE & ENVTL. L. 341 (2000).

733. Hydrogen-powered fuel cells, which would replace some fossil fuel-powered engines, are now receiving considerable attention. The Wall Street Journal said "not long ago, the fuel cell was dismissed as an environmentalist's pipe dream [but now] it is the subject of a heavily financed research-and-development race among some of the world's biggest auto makers." Jeffrey Ball, *Road Test: Automakers Are Racing to Market 'Green' Cars Powered by Fuel Cells*, WALL ST. J., Mar. 15, 1999, at A1. *See* Fred Bosselman, *Can Technology Reduce the Energy Cost of Sprawl*, 30 ENVTL. L. REP. 10,829 (Oct. 2000).

734. The Kyoto Protocol, which requires ratifying nations to severely reduce fossil fuel emissions, would only reduce the anticipated global temperature increase in 2050 from 1.4°C to 1.395°C if its goals were fully reached. Dale Jamieson, *Climate Change and Global Environmental Justice*, *in* CHANGING THE ATMOSPHERE, EXPERT KNOWLEDGE AND ENVIRONMENTAL GOVERNANCE 287, 304, (Clark A. Miller & Paul N. Edwards eds., 2001). In ecological time frames, global warming is likely to occur so quickly that changes in the ecosystem will lag several hundred years behind. FRANCES DRAKE, GLOBAL WARMING: THE SCIENCE OF CLIMATE CHANGE 209 (2000).

counteract the effects of such change.[735] One of the key recommendations of a recent National Research Council panel was to "explore prospects for mitigating these perturbations" by exploring the "feasibility and effectiveness of a variety of" technical and institutional approaches "for achieving sustainability of the essential nutrient cycles."[736]

The adoption of laws requiring environmental impact analysis has provided strong encouragement for the development of methodologies to quantify the relative environmental impacts of various alternatives.[737] Such quantification encourages the design of projects which produce an apparently favorable balance of impacts.[738] Numerous states followed the federal example and established state laws requiring environmental impact analysis.[739] Unlike the federal law, some of these state laws went further and required the showing of a positive environmental impact.[740] These statutes fostered a particular way of looking at environmental problems: focus on a particular development activity and tailor the regulation of that activity to insure that its beneficial impacts balanced or outweighed its adverse impacts.[741]

The concept of environmental mitigation was a logical outgrowth of this type of analysis. If a developer wanted to undertake a project that had adverse impacts on the environment, she could combine it with some other development activity, perhaps even wholly unrelated, that had a beneficial environmental impact,

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735. For a classification of potential trade-off mechanisms, see James Salzman & J.B. Ruhl, *Currencies and the Commodification of Environmental Law*, 53 STAN. L. REV. 607 (2000).

736. NAT'L RESEARCH COUNCIL, GRAND CHALLENGES IN ENVIRONMENTAL SCIENCES 20 (2001).

737. For an early example, see LUNA B. LEOPOLD ET AL., A PROCEDURE FOR EVALUATING ENVIRONMENTAL IMPACT (Geological Survey Circular 645, 1971).

738. *See* COUNCIL ON ENVTL. QUALITY, ENVIRONMENTAL IMPACT STATEMENTS: AN ANALYSIS OF SIX YEARS' EXPERIENCE BY SEVENTY FEDERAL AGENCIES 50-52 (1976).

739. See Donald G. Hagman, *NEPA's Progeny Inhabit the States - Were the Genes Defective?*, 7 URBAN L. ANN. 3 (1974).

740. *See* JAMES F. BERRY & MARK S. DENNISON, THE ENVIRONMENTAL LAW AND COMPLIANCE HANDBOOK 85-87 (2000).

741. A Florida statute establishing a procedure for the evaluation of developments of regional impact was of particular significance. Not only did it authorize the denial of development permission if the overall balance was found to be negative, it went significantly beyond the consideration of environmental factors to include the fiscal and economic considerations previously discussed. *See* JOHN M. DEGROVE, LAND, GROWTH AND POLITICS 119-20 (1984). The statute does not require quantification of impacts, and the Florida Supreme Court has expressly upheld the balancing of various factors without quantification, Graham v. Estuary Properties, Inc., 399 So. 2d 1374, 1377-78 (Fla. 1981), *cert. denied*, 102 S. Ct. 640 (1981), but the trade-off of positive and negative impacts has proven to be a key element of the process. *See* Gilbert L. Finnell, Jr., *Coastal Land Management in Florida*, 1980 AM. B. FOUND. RES. J. 303, 370-75 (1980); THOMAS G. PELHAM, STATE LAND-USE PLANNING AND REGULATION 49 (1979).

with the result that the balance tipped toward the favorable side.[742] Although mitigation sometimes incurs the wrath of environmental purists who brook no compromise, it has achieved widespread support from mainstream environmental organizations who see the opportunity to use the economic benefits generated by the development process as a source of funds for environmental protection that would not otherwise be forthcoming.[743]

Mitigation may be the best opportunity to cut back on some of the trends that we seem unable or unwilling to control by setting standards.[744] The idea that people who contribute to ecological collapse should bear the responsibility for mitigating the damage they create is a persuasive one.[745] But a recent study by the National Research Council found that the science and technology needed to mitigate damage to sensitive ecological systems such as wetlands must be based on large scale studies and planned on a regional basis.[746] The extensive efforts by industry to develop legal tradeoff systems to mitigate climate change is an example of efforts in that direction.[747]

3. Adaptation

Realistically, we can only hope to slow some of the future environmental change through reversal and mitigation. It will also be essential to adapt to environmental change in ways that reduce its adverse ecological impact to the extent possible. One way to do this is to develop programs that will better integrate natural ecological systems and the human environment. University of

742. For a current look at the way mitigation often works, see Thomas J. Schoenbaum & Richard B. Stewart, *The Role of Mitigation and Conservation Measures in Achieving Compliance with Environmental Regulatory Statutes: Lessons from Section 316 of the Clean Water Act*, 8 N.Y.U. ENVTL. L.J. 237 (2000).

743. *See* Lisa A. Wainger et al., *Wetland Value Indicators for Scoring Mitigation Trades*, 20 STAN. ENVTL. L. J. 413, 414-15 (2001).

744. NAT'L RESEARCH COUNCIL, *supra* note 736, at 24.

745. For a discussion of the potential uses of biodiversity impact fees, see A. Dan Tarlock, *Local Government Protection of Biodiversity: What Is Its Niche?*, 60 U. CHI. L. REV. 555, 598-602 (1993).

746. NAT'L RESEARCH COUNCIL, COMPENSATING FOR WETLAND LOSSES UNDER THE CLEAN WATER ACT 45 (2001). The report suggests that the creation or restoration of ecological systems is much easier for some types of system than for others; for example, salt marshes and wet meadows are much easier to create or restore than shrub swamps and forested wetlands. *Id.* at 22-23. The report emphasizes the need for legal requirements and administrative enforcement to assure that required mitigation is monitored and enforced. *Id.* at 138-40.

747. JAE EDMONDS ET AL., PEW CENTER ON GLOBAL CLIMATE CHANGE, INTERNATIONAL EMISSIONS TRADING AND GLOBAL CLIMATE CHANGE ii-iv (1999). "Markets for environmental commodities represent the new wave of environmental protection and, despite critiques both subtle and shrill, they are still building." Salzman & Ruhl, *supra* note 735, at 609-10.

Arizona ecologist Michael Rosenzweig has come up with a name for this idea that has the potential of becoming the kind of sound bite needed to communicate in today's culture – reconciliation ecology.[748]

The goal of "reconciling" humans with the other species of the world is not new, of course, but Edward O. Wilson, the distinguished Harvard biologist who has initiated so many new scientific concepts, stimulated renewed interest in the idea with the publication of *Biophilia*[749] in 1984. His argument that an innate love of nature has evolved in humans through natural selection has been contentious, but it has stimulated a wide range of interest in further study of the psychological and sociobiological relationship between humans and other species.[750]

Rosenzweig, who is writing a book on reconciliation ecology, summarizes his analysis of the idea this way:

> For historical reasons, conservation biology has become mired in an attitude of confrontation: The green forces of nature versus the green forces of money. Conservation divides the world into pristine habitats and ruined habitats. It tries to save and restore the former while preventing further loss . . . .
>
> Science insists that area is an intrinsic property of natural ecosystems. To maintain their diversity, they must have their area. Thus, conservation biology has to address itself to the habitats in which human beings live, work, and play. Conservation biology has to learn how to share anthropogenic habitats with wild species. It needs to discover how to modify and diversify those habitats so that they harbor a wide variety of species. I call this sort of conservation biology reconciliation ecology.[751]

Conservation biology, which is an increasingly important applied science, has always recognized the need for studying the human element in biodiversity protection, as my colleague Dan Tarlock noted back in 1993: "Conservation biology is a true paradigm shift in resource management. It rejects the traditional

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748. Rosenzweig, *supra* note 533, at 5404.

749. WILSON, *supra* note 376.

750. *See, e.g.*, THE BIOPHILIA HYPOTHESIS (Stephen R. Kellert & Edward O Wilson eds., 1993).

751. Rosenzweig, *supra* note 533, at 5409. For excerpts from Rosenzweig's forthcoming book, see http://eebweb.arizona.edu/faculty/mlro/foot.html (last visited Jan. 5, 2002).

idea of resource preservation as fencing out humans to the maximum extent possible to isolate an ecosystem and replaces it with a view that recognizes the dynamic interaction between human settlement and natural systems."[752]

Holly Doremus argues that our current emphasis on nature reserves "can impede the development of a caring human relationship with nature," because it "suggests that human intrusion can only destroy nature." It is human contact with nature, she suggests, that is "essential to building the kinds of emotional connections that lead to political support for nature protection."[753] Our discourse

> should be as much about people as it is about nature. It should explain how people can fit into nature and fit nature into their lives. It should . . . focus on ways in which frequent contact with nature can make a difference to people, and make people different. It should acknowledge that nature can, and should, be found even in places heavily modified by human action.[754]

Ecological systems will continue to change in response to human modifications of the environment. The techniques of large-scale ecology will make us more aware of the nature of those changes, but the unprecedented nature of those changes will challenge the predictive abilities of ecological science. To the extent that we cannot fully reverse or mitigate these changes, we can adapt our

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752. Tarlock, *supra* note 745, at 567. A major obstacle to biodiversity protection "is that species increasingly are imperiled by highly dispersed, impersonal, untraceable human activities." J.B. Ruhl, *State and Local Government Vicarious Liability Under the ESA*, 16 NAT. RESOURCES & ENV'T 70, 77 (2001). *See also* Gretchen C. Daily, *Developing a Scientific Basis for Managing Earth's Life Support Systems*, 3 CONSERVATION ECOLOGY (2): 14, *at* www.consecol.org/Journal/vol3/iss2/art14/ (last visited Jan. 12, 2002).

753. Doremus, *supra* note 485, at 50-51. "If progress is to be made in the law of nature protection, the political discussion must more closely address the crux of the problem, asking how humans can live with and in nature." *Id.* at 63.

754. *Id.* at 64-65. Oxford biologist Robert May also suggests that too great an emphasis on ecosystem services could undermine biodiversity because:

> deeper knowledge of the rules governing ecosystem assembly could enable "ecosystem services" to be delivered in a world which was grievously biologically impoverished. The possibility that the world of the cult movie "Bladerunner" may be sustainable cannot be ruled out just because I – and probably you – would not wish to live in it.

ROBERT M. MAY, INTRODUCTION TO THE PRINCETON LANDMARKS IN BIOLOGY EDITION OF STABILITY AND COMPLEXITY IN MODEL ECOSYSTEMS xxv (2001).

activities to the maintenance of viable ecological processes most successfully if we make a conscious effort to do so.

V. CONCLUSION

The advances in ecological science that have made it possible to study the natural world over longer time spans and on larger geographic scales are sufficiently important that we should reexamine the laws regulating management of natural resources and environmental protection to incorporate today's best scientific knowledge. This requires that we obtain and distribute ecological information widely, that we use ecological assessment procedures and develop and monitor ecological indicators, that we require that environmental analyses be done on large scales, that we plan and manage natural resources with particular emphasis on management after disturbance, and that we give equal emphasis to the ecological problems caused by action and inaction. Above all, we must use all the means available to counteract the unprecedented, unidirectional changes that we are making to ecological systems.